SATELLITE CAPABILITIES MAPPING – UTILIZING SMALL SATELLITES

THESIS

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AFIT/GSE/ENV/10-S01DL

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THESIS

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Without the support of those around us, we accomplish nothing.

David A. Grigsby

Table of Contents

Page

Page

List of Figures

Page

List of Tables

Page

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Abstract

The cost and schedule advantages small satellites have over larger legacy systems have been studied for years, but there has been very little experimentation performed to determine whether small satellites can actually deliver the capabilities of larger spacecraft. To date, a desired operational capability has not been fully realized by a scalable satellite design. Advances in sensor technology have led to significant reductions in size, weight, and power (SWaP) presenting an opportunity to exploit the evolution of space operations by using small satellites to perform specific missions. This paper describes a methodology developed to map a specific set of defined large space vehicle capabilities to a constellation of small satellites. The process includes an analysis of user needs, capability gaps, and examines the utility of advanced sensors. This leads to determining: number of satellites; orbit geometry; sensor configurations; and the satellite bus.

Space weather has been identified as an excellent mission to exploit the potential of small satellites. Advances in commercial micro-electronics have produced sensors with reduced SWaP, making them viable test subjects. Therefore, mapping capabilities to a small satellite, or constellation of small satellites, could provide solutions and affordable options to the adverse challenges facing space operations. The methodology developed here selects sensor of the National Polar-Orbiting Environmental Satellite System (NPOESS) Space Environmental Sensor Suite (SESS) and maps it to a CubeSat illustrating a small satellite can perform an operational mission.

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1. Introduction

1.1 Background

The space industry faces significant challenges in the years to come due to increasing costs and delayed schedules. In fact:

> Estimated costs for major space acquisition programs have increased by about $10.9 billion from initial estimates for fiscal years 2008 through 2013. In several cases, DOD has had to cut back on quantity and capability in the face of escalating costs. Several causes behind the cost growth and related problems consistently stand out. First, DOD starts more weapons programs than it can afford creating competition for funding that, in part, encourages low cost estimating and optimistic scheduling. Second, DOD has tended to start its space programs before it has the assurance that the capabilities it is pursuing can be achieved within available resources [1].

These cost over-runs will consume future funds if the program is kept alive, and/or lead to reducing the capability in order to control the cost. The greatest impact resulting from this trend is the loss of capabilities. The United States has invested decades of human and monetary resources to evolve our dominance in space to its current level which requires our capabilities to greatly exceed those of our adversaries. The United States definitely wants to avoid the stagnation of their space capabilities while adversaries continue to advance their own.

The entire space industry must adapt to more austere economic conditions and develop more efficient practices not only to reduce costs but deliver at the original estimate. In any other market, product lines that continually evolve their core technologies are strongest. They create the natural expectation that greater, more advanced, capabilities will continue to be produced at a lower price over time. The argument that space acquisitions and operations are more complex and difficult, thus

demanding more resources than other industries, is a hard sell when consumers can easily obtain the functionality (capability) found in today's smart phones. Of course, a smart phone and a satellite are significantly different; however, it is the evolution of technology demonstrated by smart phones that consumers and taxpayers have grown to expect. The space industry will, by default, be held to those same expectations.

In 1994, a presidential decision directive was issued combining civil and military polar-orbiting satellite systems into a single operational program known as the National Polar-orbiting Operational Environmental Satellite System (NPOESS). NPOESS was a tri-agency program with Department of Defense (DOD), National Oceanic and Atmospheric Administration (NOAA), and National Aeronautics and Space Administration (NASA). The goal was to reduce costs, duplication of efforts, and streamline schedules while developing and operating the nation's next generation of weather satellites. Unfortunately, on 1 February 2010 the president's FY11 budget dismantled the NPOESS program [2] after it had exceeded the original cost estimate by over 100% and several years [1]. The problems and impacts of the NPOESS program will be discussed in more detail in a later section.

The NPOESS program illustrates the problems plaguing space acquisitions. The dismantling of NPOESS will reduce space weather monitoring capabilities (i.e. producing capability gaps) which is a more significant impact than the lost financial investment. In April of 2010, The Government Accountability Office (GAO) released a report discussing the need for a strategy to sustain critical climate and space measurements. The report shows that federal agencies lack a strategy for the long-term provision of space weather (SWx) data [3]. "The expected gaps in coverage for the instruments

removed range from 1 to 11 years, and begin as soon as 2015" [3]. The SWx monitoring capability gap that now looms on the horizon demands a strategy that employs a process to develop a solution that addresses these needs.

"Space weather can adversely affect satellite operations, gathering of intelligence, communications, space-based and ground-based radar, Position Navigation & Timing (PNT), high altitude manned flight, and electrical power distribution grids. Space Weather support is important to the DoD because military operations are increasingly reliant on space and ground systems that are susceptible to failure or degraded performance during extreme space weather conditions. These increased user demands will drive SWx support needs to provide specifications, alerts and forecasts that have improved accuracy, timeliness, coverage, and confidence. [4]". The capability to monitor and forecast space weather needs to remain a high national priority. Without it, other capabilities utilized by both the commercial and government sectors could be impacted.

1.2 Capability Gap Looms on the Horizon

The gap resulting from the dismantled NPOESS program is not the only SWx problem facing the United States. The Defense Meteorological Satellite Program (DMSP and Polar Operational Environmental Satellite (POES) programs currently monitor and collect atmospheric and terrestrial environmental data. The final DMSP spacecraft is expected to retire in 2020 and POES will reach the end of its tenure in 2013 [5]. In 1999, the national requirements for SWx products were found to be outdated, fragmented, and incomplete. In addition, it was noted that requirements must be revised as user needs and technology evolve [4]. Not only has space acquisitions failed to evolve the requirements but also have failed to develop a strategy or process that would lead to a solution. It is

safe to say that there is an increasing sense of urgency to develop a solution to the SWx monitoring capability gap. The obvious fact is that another multiple year space acquisition program will not suffice. It's time to think outside the current paradigm.

1.3 Maturing Solution

The need to monitor SWx is evident; however, the acquisition process employed when developing and launching a satellite, let alone a constellation, has continued to disappoint. Small satellites (smallsats) have become more attractive due to their size and weight, but still have limitations, primarily related to payload capacity. Even with their limitations, smallsats have sparked interest with universities, commercial companies, and government organizations because of their ability to perform low cost on-orbit experiments and demonstrations. As their capabilities continue to mature, they present a limited solution in some mission areas of interest to the space community but at this time, certainly not all. The SWx monitoring mission has been identified as a strong potential application of smallsats [11].

Space weather sensors have advanced their capabilities while reducing their size, weight, and power (SWaP). There are several SWx sensors ranging from low to high technology readiness levels (TRLs) that are compatible with satellites as small as a nanosat (e.g. the CubeSat bus). The gap resulting from NPOESS requires a rapid solution and not another four to six year satellite procurement program.

1.4 Research Focus

The acquisition community has continued to develop satellites using the same method for several decades [1]. The DOD attempted to reform acquisitions in the 1990s by giving more oversight and key-decision making responsibilities to contractors. The

unfortunate result was less reporting which kept problems in the dark until it was too late to make the necessary changes [7].

A new approach is desperately needed; however, the beginning of an evolution in spacecraft design may have already begun simply by returning to its origins. After decades of increasing the size of a satellite to add more and more capabilities, smaller satellites are getting more attention and growing in utility. Most notable is the CubeSat bus. The CubeSat has become useful to universities, research labs, and government and private organizations as a means of on-orbit testing for sensors and performing experiments. In addition, the Defense Advanced Research Projects Agency (DARPA) is pursuing a concept known as "fractionation" which decomposes a large monolithic spacecraft into modules to be flown in clusters [8]. Thus, at this time, many efforts are trying to reduce the size, weight, and power (SWaP) of satellite payloads and separate satellites into modules, for reasons that will be discussed later in more detail. However, there is no process of mapping the capabilities of these large monolithic satellites to small sensors that could be flown on a cluster of modules or constellation of CubeSats. With several programs losing capabilities for cost and schedule reasons, it is a good time to be innovative and utilize this new paradigm to create a solution that delivers a needed capability.

While no capability mapping process can be found with that specific title, the process of mapping a capability from a large legacy system to a modern smaller system is not new. The computer electronics market has demonstrated a capability evolution process similar to capabilities mapping. Early computers, such as the xxx, were large, heavy, consumed a lot of power, and had very limited processing and storage capability.

However, the evolution and advancement of microelectronics allows all of those attributes to be reduced. Today, the capabilities available with a smartphone combine capabilities previously available by separate units and deliver better performance while being smaller, lighter and consuming less power. The evolution of technology provides a lot of promise and support to the reduction of spacecraft while maintaining various capabilities.

This thesis discusses the development of a process that maps the capabilities of a large monolithic spacecraft to one or more small satellites by taking advantage of advanced low SWaP sensors and a standardized CubeSat bus. The specific example is to deliver a representative solution to the de-manifested SESS. The process presented here will utilize advanced low SWaP sensors and use the CubeSat bus to propose performing a specific operational mission. The ability to rapidly map a capability to a small satellite that at least meets the threshold of the original requirements presents stakeholders with an option to maintain an otherwise at-risk or lost capability.

1.5 Investigative Questions

As with any new idea, the first question that is always asked is “why”. Why does the engineering community need another process to guide the development of satellites? To answer this common basic question, the process developed here is only partially new. Capabilities mapping borrows techniques from existing processes used by the engineering and acquisition community to determine specific needs and system requirements. During the formulation of an acquisition program engineers perform an analysis of alternatives (AoA) and throughout the life-cycle conduct trade studies [7]. Each tool has techniques that enable in-depth analyses of system requirements, the

resulting planned capabilities, and viable alternatives. Capabilities mapping will utilize these techniques to determine if the planned capabilities can be performed on an alternative platform, in this case a smaller platform. The revised question is, “can the system’s capability be performed by a ‘smaller’ platform with comparable results?” This is another alternative and may require trades; however it specifically and intentionally targets a smaller platform and requires a process not exactly duplicative of an AoA or trade study. In addition, the capabilities mapping process benefits from the results of the already performed analyses, e.g. system requirements, thresholds and objectives, orbital parameters. A few characteristics will change due to the size of the final solution, thus having the information that does not change will only expedite the process.

The justification and benefits for performing the capability of a large satellite on a smaller satellite has been discussed. To develop such a repeatable capabilities mapping process, a few investigative questions need to be formulated to guide the task.

Investigative Question #1:

Can a repeatable process be developed to map a large monolithic spacecraft capability to a CubeSat bus?

Investigative Question #2:

Does a sensor compatible with the CubeSats bus exist and meet the threshold performance specification of a larger system?

Investigative Question #3:

Can a constellation of CubeSats perform an operational mission?

The answer to these questions would provide a tool that would benefit the space industry. Combining this tool with the concept of "fractionated" spacecraft, discussed in a later section, could evolve the space industry into a new way of doing business.

Once created, the process will be applied to a selected sensor from the de-manifested SESS from the NPOESS program that has been noted as critical to our space monitoring mission. The capabilities mapping process will map the Thermal Particle Sensor (TPS) to a constellation of CubeSats to determine if the small sensors can perform the original mission. CubeSats have been utilized for on-orbit experiments and testing but never to perform an operational mission. The success would be twofold; the constellation would fill a critical capability gap and mark a significant advancement for the CubeSat bus.

1.6 Methodology

When a program removes a capability or recognizes one late in the program's acquisition cycle, it should not just be left behind, put on a shelf, or forgotten. Instead, if it performs a critical function or could be launched on another smaller platform at a lower cost, then a methodology should exist that enables stakeholders to develop that low-cost and simple solution.

Capabilities mapping seeks to combine the techniques of different independent analyses and processes into a sequence of steps that lead to implementing a small satellite solution. The process will perform a system decomposition to isolate the equipment that performs the capability of interest followed by a functional decomposition to separate it into its most basic functions, i.e one task per function. Of, course, an alternate low SWaP sensor must exist that is able to perform these functions. The sensor's performance will

be analyzed against the original equipment specifications (if available) or key performance parameters (KPP) to determine its utility. If the sensor performance is acceptable then it should be integrated into the required number of CubeSats, that is if more than one is required. If the performance does not meet threshold value, then a trade between the performance, cost, and complete loss of the original (or future) capability will have to be reviewed and considered by stakeholders. If stakeholders face a capability gap and a low-cost solution delivers 70% (for example) of the desired capability then perhaps it is better to field 70% than nothing at all. The integration of the sensor onto the CubeSat bus completes the process but the data received once the CubeSat is on orbit will determine if the solution is successful.

1.7 Summary

There are numerous reports and studies in addition to those used as references supporting this thesis that illustrate the cost and schedule challenges for future space acquisition programs. Increases in costs and schedules are bad but delivering fewer capabilities and, possibly, spacecraft is unacceptable [1]. The space industry needs to learn from past practices and implement backup procedures to the extent possible. The Air Force) is urgently seeking a solution to the NPOESS problems which began, and hence was visible by top level executives, in 2005. Regardless of where the breakdown occurred, a solution is needed and quickly. The opportunity created by this dilemma is the motivation of this thesis. If the process of mapping the needed but de-manifested capabilities of the SESS, or a selected instrument as a demonstrator, is successful then it could be applied to other systems for which smaller and capable sensors exist. Considering the rate at which other countries are experimenting, successfully, with small

satellites, the space industry needs to consider new acquisition practices even if it only means small satellites are considered as a backup.

This thesis will provide a process that will advance the evolution of small satellites being utilized to perform the operational capabilities of larger satellite systems. The structure for presenting this process begins with research into the growing interest in small satellites, the impact of space weather on space-based assets, innovative technology being developed by industry and academia, the evolution of capabilities in smaller packages, and lastly, a standardized spacecraft bus and components. The next part of this thesis takes this research and develops a process that maps a large-scale satellite capability to a like capability on a small satellite maintaining traceability back to the original satellite. This thesis then closes by analyzing and discussing the contribution the capabilities mapping process makes to the space acquisitions community and the body of knowledge. A recommendation for future research and next steps for the mapping process will conclude the thesis.

2. Current Research and Literature

2.1 Chapter Overview

"Today's national security satellites are a far cry from the relatively small and simple satellites that were flown in the early days of military space" [11]. The quantity of capabilities on current satellites out numbers those on legacy systems. In the pursuit of a large number of highly advanced capabilities, the spacecraft development becomes more complex, employs redundant systems to reduce risk, require longer schedules, and in the end is left with little margin for error. These are just a few of the many reasons the space industry must begin to study alternative paths by which standardized commercial off the shelf equipment can be utilized, evaluate and accept what capabilities are good enough, and apply new methods to delivering those capabilities. The space industry, academia, and the Department of Defense have engaged in many advanced research and development efforts aimed at improving various areas of spacecraft development, i.e. bus and payloads. Likewise, specific mission areas that are best suited for smaller satellites developed for specific missions have been researched and identified. A discussion of selected studies performed to understand these problems and the research attempting to provide solutions is provided in the sections that follow. The capabilities mapping process will make use of the many diverse efforts by employing the successes of academia and industry in the mapping of large-scale capabilities to small satellites and tracing back to an operational mission. By showing small satellite capabilities (sensors) have much of the same functionality in specific mission areas, the space community will continue to take more interest in smaller satellite solutions. Unfortunately, the successes with small sensors of industry and academia do not trace back to the mission area of a

comparable large, legacy system. Many academic experiments address space weather but none of them trace back to the capability on a DMSP satellite. Without that, the experiments are tried, tested, and forgotten once they de-orbit. If successful, they should be considered for an operational mission, even if only for a short duration.

2.2 The Resurgence and Utility of Small Satellites

"After some 50 years of launching large, complex, multi-million dollar spacecraft, the military and industry are rethinking the way satellites are built and acquired. The need for systems that don't take a decade to develop and deliver or can be quickly replaced is driving the trend toward smaller spacecraft" [3]. Replacing a satellite quickly with a smaller one requires reducing the scale of the current capabilities or mapping these capabilities to a smaller low SWaP sensor, if one exists. "Large satellites offer exquisite instruments and they work fabulously in orbit for a long time, but that's not necessarily the only way that spacecraft acquisitions can be done" [3].

A smallsat may be defined by different characteristics such as size, weight, power, and cost are the most common. These characteristics are proportional and any one can drive the other characteristics or find itself constrained by another. For example, a payload, e.g. instrument suite, that requires a large power supply would have an impact on the physical dimension due to the size of the power supply and required solar panels. Thus all attributes must be noted when considering desired capabilities and making decisions. The relationship among these attributes would allow parts of the satellite to be standardized; however, "manufacturers have a propensity to build a unique satellite for each specific application. The user community should encourage the development of standard interfaces and modular plug-and-play configurations. An effective approach to

minimizing the nonrecurring costs associated with new satellite developments is to emphasize distributed satellite constellations and production assembly lines. [9]" This thesis will focus on researching the utility of the CubeSat based on what was learned from various studies.

The capability and utility of smallsats have been scrutinized and while some agree that larger systems will never go away, they remain doubtful critics of the utility of small satellites. Nonetheless, smallsats are growing in popularity. While there have been studies completed to identify the problem areas plaguing spacecraft acquisitions, the utility and potential mission areas of small satellites required an analysis. Small satellites are not well suited for all missions. "Space missions can be characterized by their position in a three dimensional space defined by how much of the globe they must cover (ACCESS), how often they must view a particular spot on the earth (PERSISTENCE), and how well they must view that spot (QUALITY). Smallsats, because they offer the potential for trading persistence (by increasing constellation size) with sensor quality, naturally address different parts of this space for a given system cost. [11]" The terms above that characterize satellite missions, apply to large and small spacecraft, even as small as the CubeSat. In fact, when considering a small satellite, a concept termed "good enough" helps determine the satellite's operational utility [11]. To illustrate an example of good enough, recall the move from listening to music on compact discs (CD) to an mp3 player. When the mp3 was first introduced, the quality of the music was not as good as the original CD. A tradeoff between music quality and file size was required. Higher quality music led to a larger file size which consumed more storage. As the consumer market proves, the quality was "good enough" for the consumer to buy not only the

product but into the technology. "Finding the portions of access, persistence, and quality where smallsats can provide 'good enough' capability to satisfy realistic user needs while meeting cost constraints that result in an attractive cost-benefit is critical for establishing utility for smallsat systems. [11]" The trade between access, persistence, and quality in regards to image quality provides another example of what is good enough.

> "Combat commanders now have access to airborne electro-optical (EO) surveillance (orange bubble) that offers high resolution, great persistence, but very poor access. This leaves a lot of white space where smallsats (blue bubble) may provide capability because their cost allows persistence to be gained through numbers. The issue becomes whether or not they can deliver enough quality and persistence for a total system cost that provides good value in meeting user needs. A one meter resolution image capability of near term EO imaging satellites was "good enough" for many DoD users while a 2.5 meter resolution was deemed below the minimum capability limit. This is a good example of "good enough" trades because even though you could achieve substantially better persistence by buying twice as many 2.5 imagers, the utility remains low because of the image quality. [11]

The interest in smallsats is growing beyond the space community and is now getting the attention of ground combat commanders.

> This is often manifested in the notion of field commanders directly controlling "their" satellite. It is believed that while the warfighter-space interface does need development, ownership should be defined through unambiguous tasking authority conveyed to centralized, specially trained satellite operators who can implement them. To do otherwise will require substantial infield overhead, duplicating specialized functions such as safe satellite operations, specialized processing, etc., and requiring substantial expansion of our ground infrastructure. [11]

While the study recommends field commanders or individual soldiers should not directly task satellites, the Army is pursuing this capability in a project called Kestral Eye which will be discussed in the section that follows. "Dialog is required among users, developers, and acquirers to establish the 'good enough' that allows balance of

requirements, capabilities, and system cost. [11]" The mission areas identified by the Air Force Scientific Board as having near term operational utility are listed in Table 1.

Table 1. Small Satellite Mission Areas [11]

MISSION	NEAR TERM SMALLSAT POTENTIAL
Science & Technology	Immediate Opportunity
Space Weather	Immediate Opportunity
Weather	Mixed Architecture
Comm – Narrowband	Use Commercial Assets
Missile Defense	Possible Augmentation
Comm – Wideband	Little Potential

The board made several recommendations for Air Force Space Command (AFSPC) but the one that is most relevant to the research in this thesis is the establishment of a comprehensive capability that generates good enough requirements [11]. If the CubeSat is to perform an operational mission then it must start by identifying a specific mission, what capabilities (i.e. instruments and sensors) currently exist to provide support, and a definition of what is good enough. Establishing these parameters could also identify sensors that would benefit from additional testing or don't exist at all but are needed. To utilize CubeSats, the sensor must be within certain dimensions or, if possible, separated and integrated on multiple CubeSats and flown in formation. The space weather monitoring mission is one that has several experiments introducing or maturing many sensors compatible with the CubeSat bus. "The smallsat approach is particularly timely and critical as there is a looming crisis in the U.S. space weather

capabilities because the Space Environmental Sensor Suite is no longer manifested on NPOESS. To meet AF requirements beyond the DMSP era, a smallsat constellation could be efficiently carried out independent of other missions and systems" [11]. Space weather phenomena and its impact on space systems will be discussed later. The next step is to discuss the current research and experimentation by academia, industry, and the Department of Defense.

2.3 Advanced Concepts and Experimentation with Small Satellites

The increased attention toward small satellites has led to several experiments aimed at advancing the smallsat subsystems and small payload sensors in several mission areas.

"The Dynamic Ionosphere Cubesat Experiment (DICE) consists of two identical Cubesats with three scientific objectives: Investigate the physical processes responsible for the formation of the midlatitude ionospheric Storm Enhanced Density (SED) bulge in the noon to post-noon sector during magnetic storms; investigate the physical processes responsible for the formation of the SED plume at the base of the SED bulge and the transport of the high density SED plume across the magnetic pole; investigate the relationship between penetration electric fields and the formation and evolution of SED. [10]" DICE is one of many smallsat missions with a scientific motive. It demonstrates the ability to obtain space weather information from sensors onboard a CubeSat. "The mission will provide simultaneous key electric field and electron density measurements in the early afternoon sector where many of these events seem to form. [10]" DICE also shows how a CubeSat can complement another spacecraft's mission, in this case DMSP. "Currently, a lack of afternoon sector electric field measurements exist because the sun-

synchronous DMSP orbits are at local times that are not able to make SED coincident measurements. DICE will provide dayside electric field measurements across a broad swath of local times. [10]" The DICE constellation will employ two instruments: the Electric Field Probe (EFP) for electric field measurements and the fixed-bias DC Langmuir Probe (DCP) for absolute ion density measurements. These instruments draw on more than 20 years of sounding rocket and orbital flight heritage at Utah State University (USU) Space Dynamics Laboratory (SDL) [10]" DICE will experiment with measuring atmospheric conditions (electric field, ion density) impacted by space weather phenomena using instruments with a long history and demonstrate the technology on a CubeSat. The EFP itself is an experiment by USU students attempting to develop a Miniature Wire Boom System that fits into a standard CubeSat bus and not only takes electric field measurements but contributes to the stability of the spacecraft [11]. The Boom System nearly combines (or maps) two capabilities into one, i.e. a contributing stability capability for the spacecraft subsystem and electric field measuring capability

Table 2. DICE Science to Mission Functionality Requirements [10]

MEASUREMENT REQUIREMENTS	INSTRUMENT REQUIREMENTS
Measure RMS Fluctuations in Electric Field and Plasma Density: 1. Make co-located DC electric field and plasma density measurements at a ≤ 10 km on-orbit resolution. 2. Make AC electric field measurements at a ≤ 10 km on-orbit resolution. 3. Make measurements on a constellation platform of ≥ 2 spacecraft that are within 300 km.	Electric Field: 1. Max range of ± 0.6 V/m 2. Min threshold of 0.6 mV/m 3. Min resolution of 0.15 mV/m 4. DC sample rate ≥ 4 Hz 5. AC sample rate ≥ 4 kHz Plasma Density: 1. Range of $2x10^9 – 2x10^{13}$ m^{-3} 2. Min resolution of $3x10^8$ m^{-3} 3. Sample rate ≥ 1 Hz

for the sensor payload. “DICE is expected to launch no sooner than 2011. [10]” There is no documentation that suggests any attempt or intention to advance the DICE experiment to an operational space weather mission.

“DICE will use the PEARL platform developed by SDL to provide all of the necessary scientific, power, data processing, communications, and attitude control resources. The PEARL mission is a 1.5 CubeSat program that heavily relies on flight-proven CubeSat community components from various manufacturers, e.g. Pumpkin Inc., Honeywell, Clyde Space Ltd., etc. [10]” The PEARL mission/program has additional objectives, building the CubeSat bus toward an operation mission (Figure 1). PEARL recognizes the mindset that is different for operational missions than for scientific missions (Figure 2) [12]. PEARL seeks higher satellite subsystems capability by taking a different approach that includes requirements-based design [12]. If the existing capabilities of the satellite subsystems are the targeted area of improvement, then those capabilities should have existing requirements. Thus, researching and obtaining the requirements that led to the development of the original capability of interest will allow the focus to be on understanding what the capability provides and how it functions. It is the ability to better perform the task (e.g. attitude control) intended for CubeSat that should be focal point, i.e. an improved and reduced capabilities-based design or process of mapping the ability to the CubeSat.

Electro-optical solutions utilizing smallsats was discussed above and is an area that is being explored by academia and the Department of Defense. “The Kestral Eye program will extend the Unmanned Aerial Vehicle (UAV) paradigm into space: a dramatically lower unit cost and proliferated numbers of satellites enabling the system to

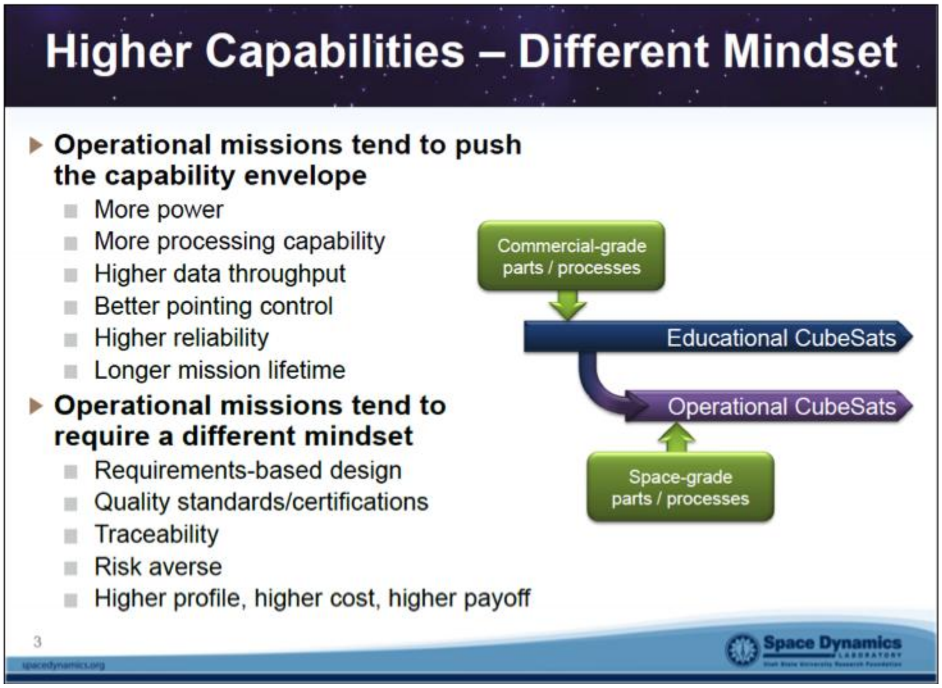


Figure 1. PEARL Mindset [12]

Figure 2. PEARL Mission Needs [12]

be dedicated to and operated by Warfighters. The eventual goal is persistent coverage available to every Soldier on a handheld device. The CONOPs for this experiment involves very small satellites, laptops, and S-Band receiver antennae (Figure 3). [13]"

Table 3. Kestral Eye Summary [13]

• Nanosatellite technology demonstrator weighing about 10 kg	• Operational life of greater than one year in Low Earth Orbit
• Electro-optical imaging satellite with 1.5 meter ground resolution	• Tactically responsive: Ability to task and receive data from the satellite during the same pass overhead
• $1M per spacecraft in production mode	

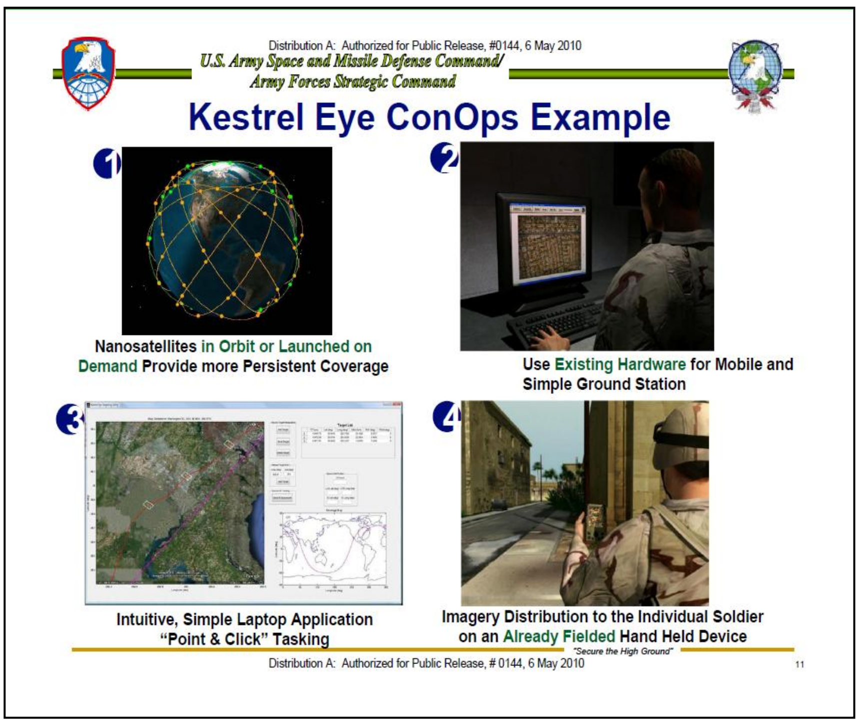


Figure 3. Kestral Eye CONOPS [13]

DARPA has introduced a concept called "fractionated satellites." Known as the F6 (Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange) program, "Fractionation is used as a term of art to describe the decomposition

of a system, here a spacecraft, into modules which interact wirelessly to deliver the capability of the original monolithic system. Fractionated architectures offer the post-design option of substituting a module, augmenting the system with an additional module, removing a module from the system, or porting a module from one system to another. [8]" Whether the module contained a subsystem capability or payload sensor capability, this system offers flexibility to spacecraft developers. If a new capability was needed or became available it could easily be added to the system or phased into a larger architecture. "One program goal of the F6 program is to develop an F6 Developers Kit that provides open interface standards and reference displays" [15]. This flexibility aids the process of mapping a capability and its individual functions to one or more modules. The open interface standards and reference displays save development time allowing the focus to remain on mapping and scaling the capability of interest. "Thus the key distinction between a fractionated and monolithic system is that the former retains elements of design flexibility throughout the operational lifetime of the system. This flexibility, in turn, provides robustness to the various uncertainties the system may encounter. [8]" Boeing completed an exercise in fractionation, they called segmentation, of a communications satellite. They found that spacecraft subsystems are physically interacting and inter-dependent for both monolithic and fractionated [16]. The exercise took existing subsystem components and segmented them into "appropriately-sized fractionated blocks". The segmentation only separated the physical components which limits the reduction because of the actual size of individual components. The exercise would be better served if the function of each system was separated. This would reveal that the CubeSat addresses various subsystem components as illustrated by PEARL

above which would allow more attention to be given to the payload. Then each function could be mapped to a low SWaP sensor compatible with the CubeSat. If one did not exist then the design requirements could be determined by the original function requirements which come from the system requirements.

2.4 Emerging Standardized Equipment

There is a spacecraft bus that has emerged as a standard. "The CubeSat is a standardized miniature satellite measuring 10 x 10 x 10 cm, weighing up to 1 kg and was developed primarily for use as an education tool. The general concept for such a satellite arose in 1998 as a result of work by students at Stanford University's Space Systems Development Laboratory" [17]. The standardized dimensions were not established at first. "Following the success of an Aerospace mission called Orbiting Picosatellite Automated Launcher (OPAL), a member of the faculty realized changes were necessary in order to make the student program successful. First, development time had to be shortened and second launch cost would have to be reduced" [17]. The reduced development time allows the capabilities to be integrated more quickly and get the satellite to orbit sooner which benefits the users. To reduce the launch cost, the faculty pursued a restriction on a characteristic of the process and equipment not so intuitive. "If the size of the satellite was reduced, that would limit the number of experiments that students could fly" [17]. This limitation of experiments is analogous to "locking" the requirements of a traditional space acquisition program. Allowing fewer requirements equates to fewer capabilities or separated capabilities. "The question that followed the idea of limiting experiments became, 'How much could you reduce the size and still have a practical satellite?'" [17]. While the decision was made to have a 10 x 10 x 10 cm

cube, the question could be expanded to include more than an experiment and practical satellite, i.e. “How much could you reduce the size and still perform an operational mission?” Table 1 lists some of the unique positive and negative characteristics of the CubeSat. The CubeSat dimensions mentioned above have been accepted and now allow a payload that can be expanded by combining additional units, e.g. 2U refers to a CubeSat that measures 10 x 10 x 20 cm and 3U measures 10 x 10 x 30 cm. The standardized bus, with an initial weight of 1 kg. will save development time by eliminating the development required for a spacecraft bus. In addition, the CubeSat could be utilized as a quick response to capability needs or gaps and to fullfil the request for a specific capability. The capability mapping process will assist by isolating the specific functions of the capability and mapping them to the functions of a low SWaP equivalent. These advantages make the CubeSat a viable platform for rapidly delivering a satellite or constellation that will perform a needed or requested capability. As discussed later, the CubeSat could serve as a platform for space weather sensors that could be flown in a constellation and fill the NPOESS SESS gaps. “At the heart of any conventional satellite design is the satellite bus, which provides mechanical support for the payload and interfaces to all power, command/data handling, communications, and computing functionalities, as well as propulsion subsystems for orbit maneuvering capability and attitude/pointing control. Many factors enter into the cost/performance ratio and cycle time required to build a spacecraft, but making a good decision regarding the spacecraft bus is vital. [11]” The CubeSat has made those decisions already. The next step is to find or develop low SWaP sensors compatible with the CubeSat bus. Low SWaP sensors offer alternatives that reduce costs and shorten development time; however, it is the low

cost of launching several that offers an even bigger benefit which is global coverage. This means providing the capability to more geographic areas and hence customers at a fraction of the cost of large spacecraft. There is an increasing demand for capabilities in specific theaters by commanders as mentioned above with the Army's Kestral Eye program. The CubeSat solves the problem of a standardized bus but there is still the dilemma of getting, i.e. mapping, the capabilities from the large spacecraft to the CubeSat.

2.5 Space Weather Forecasting and Monitoring

Space is a hostile environment. The phenomena resulting from solar emissions can negatively impact the operation of any space system. However, the space environment is better understood today than ever before, but the sun's activity is continuous and always producing phenomena that will put the operational mission of any

Table 4. Positive and Negative Issues Related to the CubeSat Size [7]

Positive	Negative
• The frame is of a simple shape and construction • Limited area for solar cells reduces manufacturing costs since the solar panels are the most expensive components for a small satellite • Low weight which allows it to be combined with other CubeSats in a single launch helping to defray costs • Take advantage of new technologies for consumer electronics such as cell phones and other portable devices • Size can be increased by combining two or three units end to end and are defined as 1U, 2U, 3U	• Limited capability because no proven attitude control systems are available • Surface area for body-mounted solar panels is limited • Subsystem requirements limit payload volume

space system at risk. This makes space weather monitoring and forecasting a critical mission in regards to space assets. Without the ability to monitor and forecast space weather phenomena, our satellites would become vulnerable which ultimately puts our national security at risk. The discussion that follows provides a discussion of space weather phenomena and impacts, space weather monitoring and forecasting user needs, capability gaps resulting from the dis-mantled NPOESS program, and the potential solutions offered by small satellites.

"The primary force in our corner of the universe is our sun. The sun is constantly radiating enormous amounts of energy across the entire electromagnetic spectrum containing x-rays, ultraviolet, visible light, infrared, and radio waves. The sun also radiates a steady stream of charged particles – primarily protons, electrons, and neutrons – known as the solar wind. [18]" When the energy and charged particles impact the Earth's atmosphere they interact with spacecraft. The effect of these interactions can negatively impede the operation of the spacecraft. "Space weather effects have the most impact on communications, Position, Navigation, and Timing (PNT), and Intelligence, Surveillance, and Reconnaissance (ISR). [4]" For example, solar energetic particles accelerated by a coronal mass ejection (CME) or solar flare can damage electronics onboard spacecraft through induced electric currents, as well as threaten the life of astronauts. Also, changing geomagnetic conditions can induce changes in atmospheric density causing rapid degradation of spacecraft altitude in Low Earth orbit. The space weather effects will always present a threat to the operational mission of those systems. The forces that protect our country's national security and interests rely on those systems. Therefore, it is important to emphasize that information on the space environment is of

paramount interest to the war fighter [18]. The impacts resulting from the three main categories of solar emissions are summarized in Table 5.

Table 5. Solar Radiation Particle Types and Effects [18]

SOLAR EMISSIONS	PHENOMENA	SYSTEM IMPACT
Electromagnetic Radiation • Arrival: immediately • Duration: 1-2 hours	• X-Rays • EUV • Radio Bursts	• Satellite communication interference • Radar interference • Long-range aid to navigation (LORAN) errors • Absorption of HF radio communications
High Energy Particles • Arrival: 15 minutes to a few hours • Duration: days	• Proton Events	• Satellite disorientation • Physical damage • LORAN errors • False sensor readings • Absorption of HF radio signals
Low- to Medium-Energy Particles • Arrival: 2-4 days • Duration: days	• Geomagnetic Storms	• Spacecraft electrical charging • Drag on low-orbiting satellites • Radar interference • Space tracking errors • Radio wave propogation anomolies

Since space weather can produce negative effects on spacecraft, there is clearly a need to understand, monitor, and forecast space weather. The military, commercial, and civil sectors have spacecraft performing missions ranging from data collection supporting the national security of the United States to providing GPS directions to millions of travelers across the country. In June 1999 the "Space Weather Architecture Study" was completed to evaluate the ability of the projected baseline support system to mitigate space weather impacts [4]. The study identified and assessed the operational impacts that would be caused by space weather effects. Today the report still serves as a starting point

when developing a space architecture that directly studies space weather or uses the data collected to provide support to other space systems.

The significance of these impacts is best illustrated by our reliance on space systems. The role of satellite operations has expanded to include an active role in addition to a support role [4]. For example, “In the future, terrestrial weapons will be directly targeted using space” [4]. The Space Weather Architecture Study stated “future National Security operations will require improved capability to accurately locate targets, provide precision navigation, and provide reliable mobile communications in a more time-constrained environment” [4]. Today, over ten years later, our dependence on space systems remains at a critical level providing evidence that it is equally critical to not only monitor and forecast space weather but also to better design satellites to resist these impacts.

As space systems age or near the end of their tenure, gaps are created if a replacement system is not launched to take its place of the old system. The needs and gaps serve as guidance to the studies that determine what direction stakeholders should take when preparing to procure a replacement system that will span several years, possibly a decade. As discussed in the introduction, NPOESS (Figure 4) was intended to be the next generation space weather monitoring system but was dis-mantled due to significant budget and performance problems.

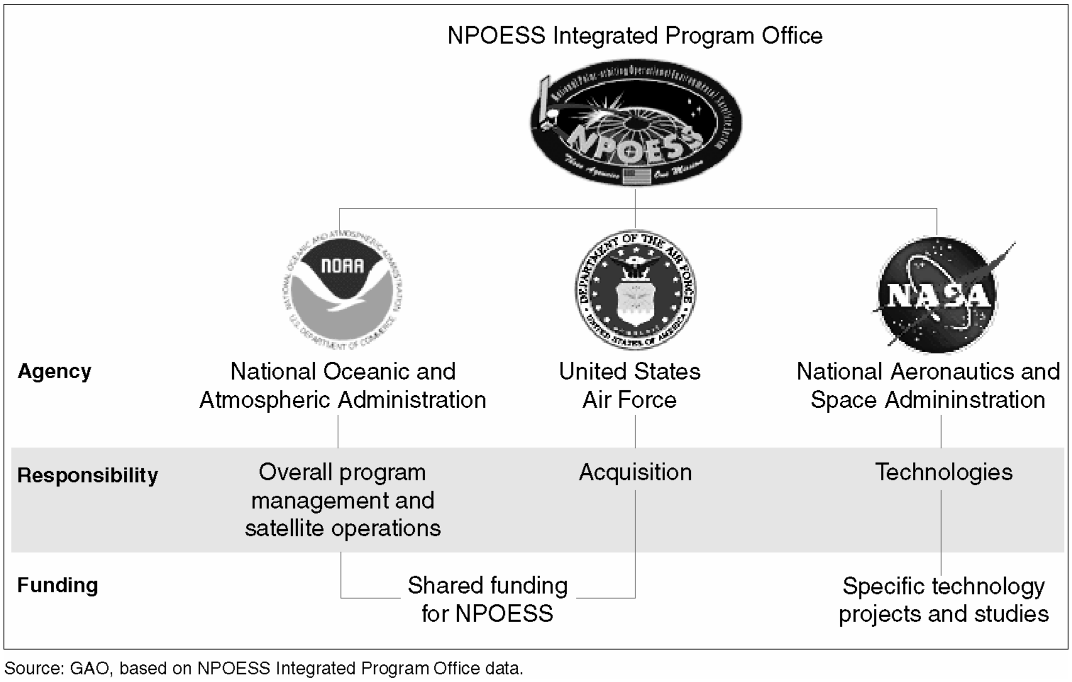


Figure 4. Organizations Coordinated by the NPOESS Integrated Program Office [20]

The importance of space weather monitoring, problems resulting from the NPOESS program, and the acquisition of spacecraft have been studied and identify mission areas for small satellites and the urgent need for a strategy that maintains continuity of space weather monitoring. A review of these studies will reveal a path to be taken in order to provide a viable and operational small satellite solution. An understanding of the magnitude of the NPOESS problem and the mitigation being taken to provide a solution will reveal potential smallsat, i.e. CubeSat, missions.

2.6 Space Weather Dilemma and Potential Mitigation

"The United States currently operates two operational polar-orbiting meteorological satellite systems: the Polar Operational Environmental Satellite (POES) series, which is managed by NOAA, and the Defense Meteorological Satellite Program (DMSP), which is managed by the Air Force. The POES and DMSP programs provide

data that are processed to provide graphical weather images and specialized weather products. They also provide the predominant input into numerical weather prediction models, a primary tool for forecasting weather" [19]. The NPOESS was a tri-agency program intended to develop and operate the next generation of weather satellites. "At the time the offices merged, they continued with plans to launch additional Polar-orbiting Operational Environmental Satellite (POES) and Defense Meteorological Satellite Program (DMSP) satellites" [20].

Program acquisition plans called for the procurement and launch of six NPOESS satellites over the life of the program. The NPOESS launch schedule was driven by the requirement of using the first NPOESS satellite to back up the final POES satellite launch in March of 2008 and the second NPOESS satellite to back up the final DMSP satellite in October of 2009 (Figure 5). The first NPOESS satellite scheduled for launch in May of 2006 was actually a demonstration satellite that would have hosted three critical NPOESS

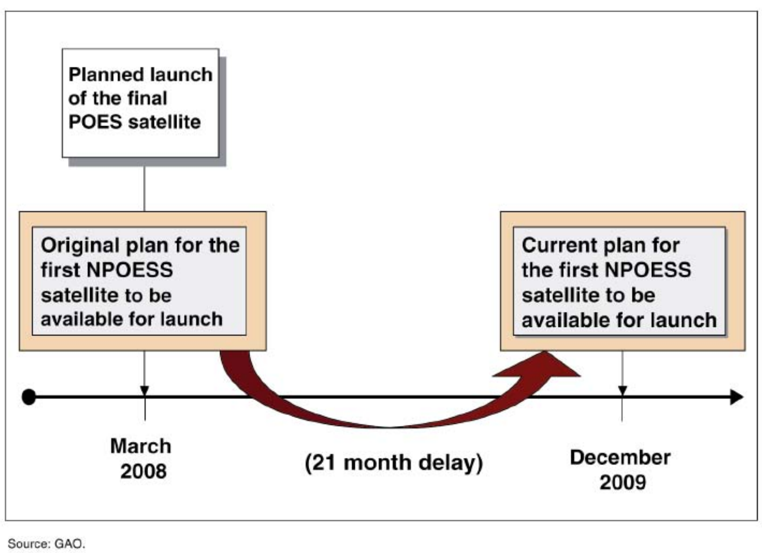


Figure 5. Timeline of Delay in Launch Availability [20]

sensors [20]. The satellites would integrate ten environmental sensors. "Seven of those sensors involved new technology and the program office considered four to be critical. [20]" However, as of August 2008 the demonstration satellite, referred to as the NPOESS Preparatory Project (NPP), had not launched and is currently scheduled to launch in the third quarter of 2010 (NPOESS Program Status, August 2008).

"In August 2005, the NPOESS program office determined that it could not execute its planned program within the constraints of its current baseline. In November of 2005, it was determined that at completion the final program cost would be 25% greater than its baseline" [20]. This breach required the program to be certified under the Nunn-McCurdy Act. In December of 2006, a joint document released by NASA and NOAA outlined the impact of the certification; however, the NPOESS program would have to be de-scoped if it was to survive. Unfortunately, on 1 February 2010, the president's FY2011 budget announced a major restructuring of the NPOESS program. The program was reported as being "behind schedule, over budget, and underperforming" [2].

The concerns resulting from the Nunn-McCurdy Certification are clear and valid. The Space Weather Architecture Study recommended three space weather architectures to satisfy all the 2010-2025 user needs. Unfortunately, not even the "Desired Architecture" (Figure 6) alternative will satisfy all the user needs. This combined with the dismantled NPOESS program prove there will be gaps in the 2010-2025 period. Thus, the need for an interim, possibly even long-term, solution is needed.

The Space Environmental Sensing Suite (SESS) raised concerns when it was removed from NPOESS in 2005. "The SESS consists of sets of sensors that provide data

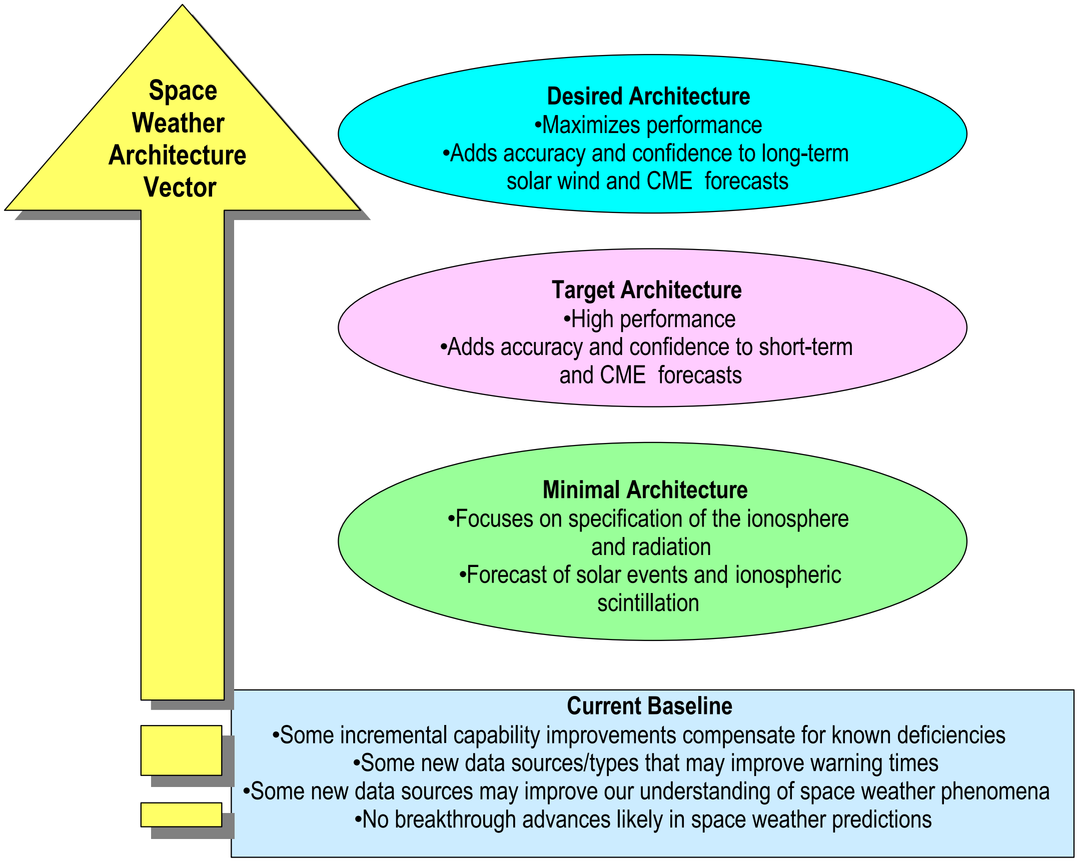
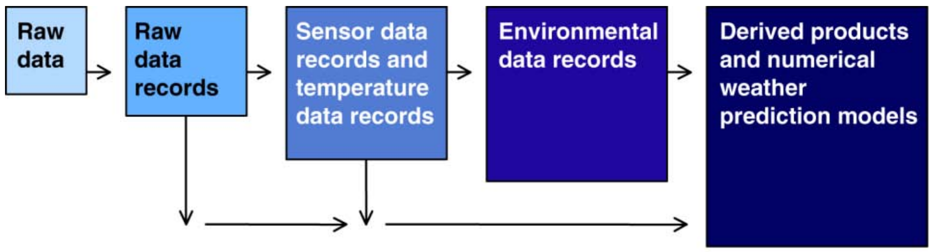


Figure 6. Space Weather Architecture Vector with Progressive Capability [4]

on electron density profiles, neutral density, geomagnetic field, precipitating electrons and ions, electric field/ion drift velocity, radiation dose, neutral atmosphere, galactic cosmic rays, trapped particles, ionospheric scintillation, auroral emissions, in-situ plasma measurements and other selected space environmental parameters. [21]" The SESS supported 13 environmental data records (EDR). "EDRs range from atmospheric products detailing cloud coverage, temperature, humidity, and ozone distribution; to land surface products showing snow cover, vegetation, and land use; to ocean products depicting sea surface temperatures, sea ice, and wave height; to characterizations of the

space environment. Combinations of these data records (raw, sensor, temperature, and environmental data records) are also used to derive more sophisticated products, including outputs from numerical weather models and assessments of climate trends (Figure 7). [22]"



Source: GAO.

Figure 7. Satellite Data Processing Steps [22]

Figure 8 below lists the EDRs produced from data obtained from sensors in the SESS. "It shows current capability, Pre-Nunn McCurdy (NM) NPOESS, and Post-NM NPOESS space environmental sensing performance and capability (Figures 9-10). As shown, only one of the thirteen EDRs will be satisfied Post-NM, four will be degraded,

NPOESS Integrated Operational Requirements Document – II (IORD-II)
Space Environmental Sensing Requirements

Environmental Data Records (EDR)	Current capability (Includes: DMSP, POES, METOP, CNOFS, and COSMIC)	Pre-NM performance Compared to IORD-II Nunn-McCurdy Certification (NM)	Post-NM performance compared to IORD-II
Electron Density Profile	Y	Y	R
Energetic Ions	Y	G	Y
Ionospheric Scintillation	Y	Y	R
Auroral Energy Particles	G	G	Y
Neutral Density Profile	Y	Y	R
Auroral Energy Deposition	G	G	Y
Medium Energy Charged Particles	Y	G	Y
Electric Field	Y	G	R
Auroral Imagery	G	Y	R
Geomagnetic Field*	Y	Y	R
Auroral Boundary	G	G	G
In-situ Plasma Temperature	G	G	R
In-situ Plasma Fluctuations	Y	G	R

R- No capability Y-Degraded G-Meets Requirements

IORD-II requires a 90 min latency or better for all EDRs
* Magnetometer demanifested prior to NM

Figure 8. NPOESS Space Environmental Requirements Satisfaction [23]

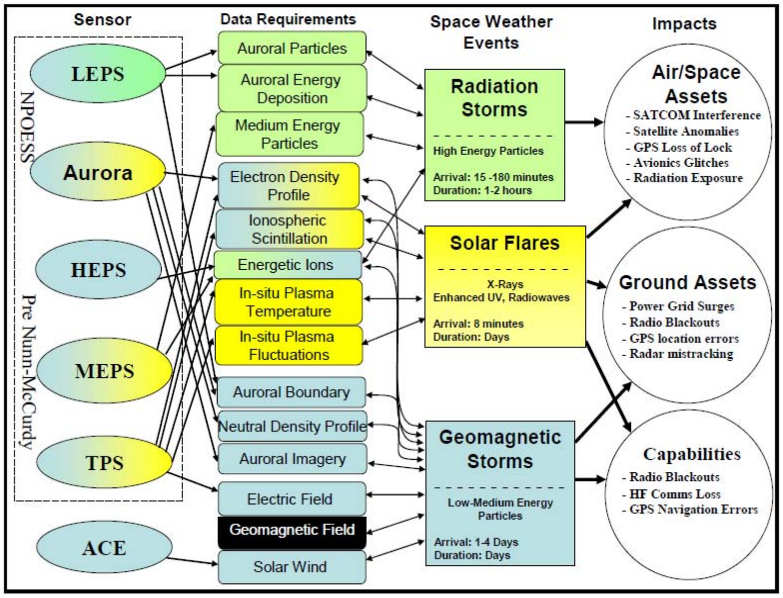


Figure 9. Traceability of Pre-Nunn McCurdy NPOESS SESS to space EDRs [5]

and five will no longer exist" [5].

Returning to the earlier discussion of the impacts of space weather, the capabilities now absent are listed in the table below.

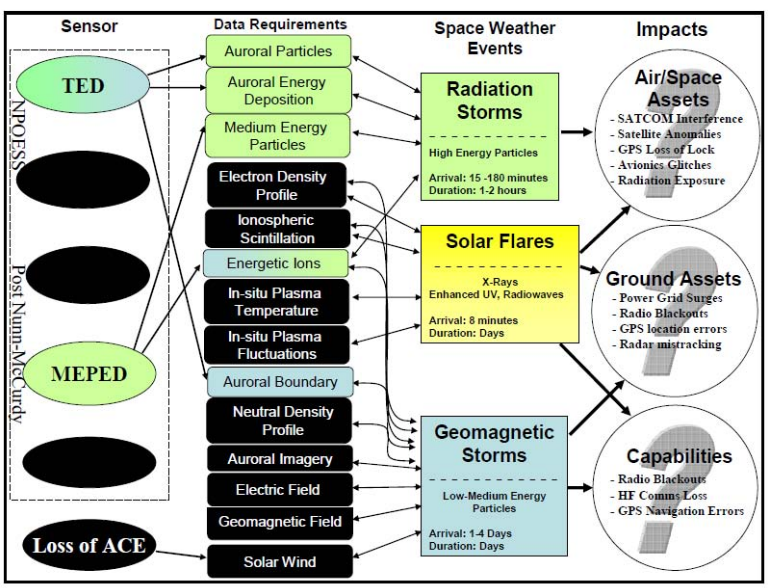


Figure 10. Traceability of Post-Nunn McCurdy NPOESS SESS to space EDRs [5]

The SESS contained five instruments: Low Energy Particle Sensor (LEPS), Medium Energy Particle Sensor (MEPS), High Energy Particle Sensor (HEPS), Thermal Plasma Sensor (TPS), and Airglow & Aurora Ultraviolet Remote-sensing Observations for Real-time Applications (AURORA). Each sensor is briefly described in Table 6.

Table 6. SESS Sensor Descriptions [5]

SENSOR	DESCRIPTION
Low Energy Particle Sensor (LEPS)	The LEPS will measure mostly auroral and supra-thermal particles precipitating into the upper atmosphere at mid-to-high magnetic latitudes. The LEPS was the primary sensor for measuring the equatorial Auroral Boundary and the Auroral Energy Deposition EDRs.
Medium Energy Particle Sensor (MEPS)	The MEPS measures the differential energy fluxes of electron and protons at 0 degrees and 90 degrees relative to the local vertical. It is the primary sensor for measuring the Medium Energy Charged Particle EDR and supporting sensor for measuring the Auroral Boundary and Auroral Energy Deposition EDRs, as well a contributing to the Electron Density Profile EDR.
High Energy Particle Sensor (HEPS)	The HEPS measures the precipitating flux of high energy ions into the atmosphere. It is the primary sensor for providing the Energetic Ions EDR.
Thermal Plasma Sensor (TPS)	The TPS is actually a set of plasma collectors used to measure and characterize the densities, temperatures, and drifts of the thermal ionospheric plasma at satellite altitude. The TPS satisfies the Electric Field, In-situ Plasma Temperature and In-situ Plasma Fluctuations EDRs. TPS also contributes to the Electron Density Profile EDR.
Airglow & Aurora Ultraviolet Remote-sensing Observations for Real-time Applications (AURORA)	The AURORA sensor provides remotely-sensed data from the ionosphere and thermosphere by observing Far Ultra Violet (UV) emissions from atmospheric constituents. The primary data products for the AURORA are the Electron Density Profile, Neutral Densiy Profile, and the Auroral Imagery EDRs.

The impact resulting from the de-manifested sensors has prompted several recommendations to mitigate the loss of space environmental sensors [11]. The responsible committee developed an incremental approach made up of four increments, figure x, from bare baseline capability to the full architecture.

As shown in Figure 11, the original capability will not be fully restored until 2017. In addition, there are no new technologies introduced, i.e. those being experimented with that were discussed above. "When the NPOESS program breached

Increment Name	Increment Initial Capability Coverage Period 2014-2024	Risk	Cumulative Cost ($M)
Increment 0: Baseline	2014	Low	$87
Increment 1: Legacy	2016	Low	$1,002
Increment 2: IORD Threshold	2017	Moderate (Cost)	$1,843
Increment 3: Objective Architecture	2020	Moderate (Cost & Technical)	$3,274

Performance vs IORD Requirement	Current capability	NPOESS Pre-NM	NPOESS Post-NM	Increment 0: Baseline	Increment 1: Legacy	Increment 2: IORD Threshold	Increment 3: Objective Architecture
Electron Density Profile	Y	Y	R	Y	Y	G	B
Energetic Ions	Y	G	Y	Y	Y	G	G
Ionospheric Scintillation	Y	Y	R	Y	Y	G	B
Auroral Energy Particles	G	G	Y	Y	G	G	B
Neutral Density Profile	Y	Y	R	R	Y	G*	G*
Auroral Energy Deposition	G	G	Y	Y	G	G	B
Medium Energy Charged Particles	Y	G	Y	Y	Y	G	G
Electric Field	Y	G	R	Y	Y	G	G
Auroral Imagery	G	Y	R	R	G	G	B
Geomagnetic Field	Y	Y	R	R	Y	G	G
Auroral Boundary	G	G	G	G	G	G	B
In-situ Plasma Temperature	G	G	R	Y	G	G	G
In-situ Plasma Fluctuations	Y	G	R	Y	Y	G	G

Legend	R-No capability	Y-Degraded	G-Meets Reqmts	B-Exceeds IORD Threshold Reqmts

Figure 11. Summary of Performance, Risk, Schedule, and Cost by Increment. [23]

cost and schedule thresholds in 2006, it was restructured and most of the space environmental sensing capability was removed to reduce cost. Without action to restore this capability, the nations space environmental sensing capability will fall to pre-1980 levels in approximately 2020 when the last DMSP spacecraft reaches end of life. [11]" Mitigation efforts have begun, but they do not utilize any of the space weather sensors or methods being developed as discussed in the sections above.

If the SWx sensor be used in the experiments by academia, government labs, and industry were to be utilized with the CubeSat bus then maybe a quick, good enough solution could be obtained at a low cost. The experiments that employ the low SWaP

sensors have been producing impressive results and the CubeSat bus is becoming a bus of choice due to its cost and short development cycle. The success would recommend the two be exploited by the larger program offices and corporations. The two could be joined if a method were to demonstrate the successful mapping of the large-scale capabilities to the experimental low SWaP sensors.

2.7 The Trend of Advanced Capabilities in Smaller Packages

Consumers continue to enjoy products that provide numerous capabilities that are smaller, lighter, consume less power, and typically offer an increase in performance than the predecessor. The computers used everyday by most Americans is the best example. All of these are true of satellites with the exception of cost and schedule. The commercial market will always exceed satellites in regards to cost and schedule performance; however, "science and technology developments in the various bus subsystems (power, structures, attitude control, propulsion, command and data handling, thermal, and communications) and payloads (e.g. telescopes, radio-frequency [RF] electronics, laser communications) have enabled a significant increase in space systems capabilities. Six satellite technologies or subsystems have been analyzed, over the last 10 to 25 years, to examine the relative trends of those technologies. [9]" The reduction in size, weight, and power along with the advancements in nanotechnology and miniaturized components, present small satellites, i.e. CubeSats, with a probable operational mission in the near future.

"The specific reductions in satellite weight coupled with similar progress in other satellite subsystems and components have reduced satellite weight by a factor of about two every eight years since 1981. This shrinking satellite trend is not evident because the

benefit of the weight savings is used to significantly increase capabilities. [9]" As stated earlier, the increase in capabilities in larger spacecraft has negatively impacted cost and schedule. These cost and schedule overruns typically result in the program cutting capabilities. Capabilities should never be eliminated if they are ready to fly. Instead, they should be considered for smaller platforms, hence the interest in smaller satellites with fewer capabilities. A situation such as this needs a method that would map that capabaility to a smaller satellite. CubeSats and low SWaP sensors present a new alternative while being beneficiaries of the increase in performance for lower SWaP as in Figures 12-15. Unfortunately, there is no method practiced to map the needed capabilities to a small satellite such as a CubeSat.

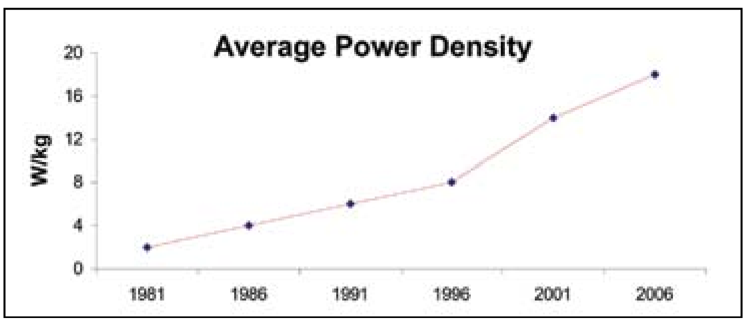


Figure 12. Average power density in watts per kilogram for spacecraft electrical power system. [9]

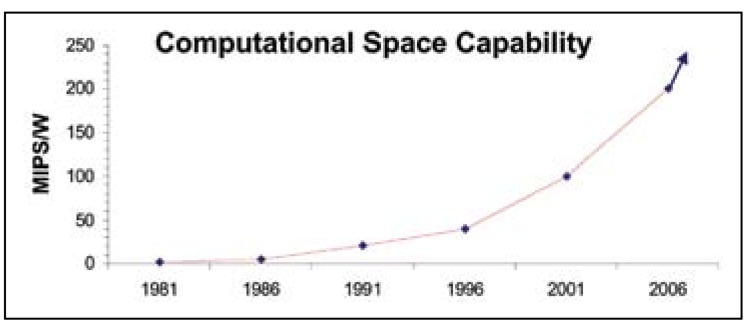


Figure 13. Millions of instructions per second capability per unit [9]

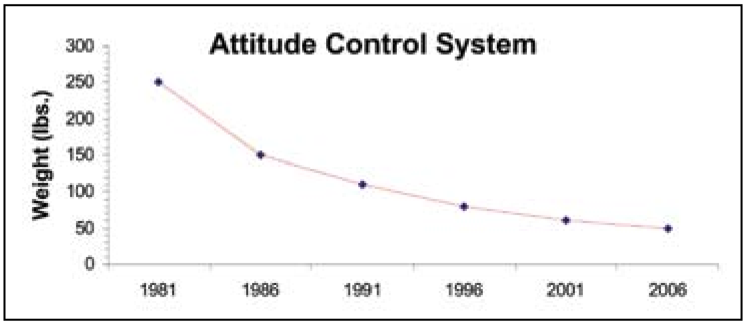


Figure 14. Relative weight of a spacecraft attitude control system for a fixed capability [9]

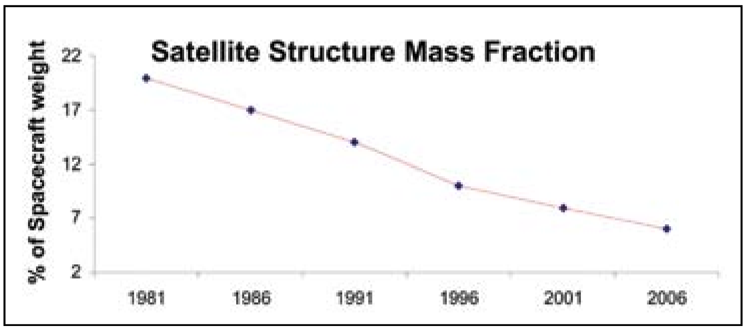


Figure 15. Percentage of satellite structure mass fraction [9]

Another example of a "big thing (capability) in a small packages is the Pico projector. [24]" The PicoP ® is a display engine developed by Microvision that is intended to fit inside of a handheld device, e.g. smartphone (Figure 16). "The architecture is quite simple, consisting of one red, one green, and one blue laser, each with a lens near the laser output that collects the light from the laser and provides a very low numerical aperture beam at the output. The light from the three lasers is then combined with dichroic elements into a single white beam. The complete projector engine is 7 mm in height and 5 cc in total volume. [24]" The Pico projector by Microvision illustrates a reduction in a capability other than space weather sensors proving that miniaturized components and their applications support opportunities for

smallsats in numerous markets and mission areas. “The scanned laser projector paradigm provides a path forward to higher-resolution projectors without growth in size. [24]”

The last area to be discussed that presents numerous and diverse opportunities for smallsats is nanotechnology and miniaturized components. “In addition to the continuing advances in traditional technology areas over the last 25 years, significant improvements can be made by integrating nanotechnologies, micro-sensors, and miniaturized components. They are essential to enable our new generation satellites, allowing for vastly increased capabilities and smaller and lighter satellites. The three areas of nanotechnology (materials, electronics/computing, sensors/components) provide powerful (in the petaflops range), compact, low-power, radiation hardened onboard computers, allowing for autonomous intelligent vehicles. [20]” Nanotechnology may be

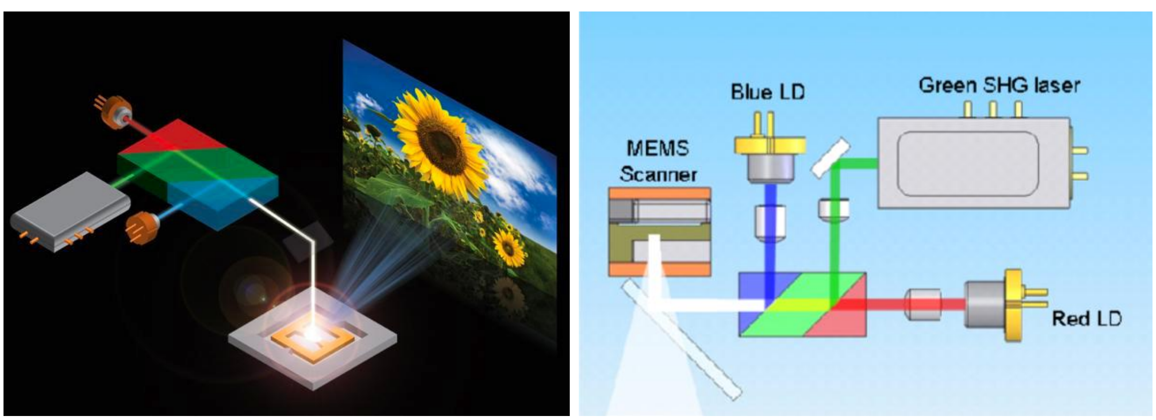


Figure 16. Scanned laser: A simple projector design [24]

the next phase in the evolution of smallsat payloads, i.e. taking the experiments discussed above (DICE, Fractionated spacecraft, etc.) to an even more advanced level not only making them smaller but more capable. The functions of the capabilities that result from nanotechnology introduce possible solutions to any market that desires a reduction in the

SWaP of their product. The interest in small satellites would benefit from a method that identifies subsystem or payload functions in order to determine if some type of nanotechnology could produce an alternative with low SWaP. The Pico projector demonstrates an achievement toward reducing the SWaP of one specific capability. If the space industry embraced the same innovative thinking then it too could see a reduction in the SWaP of spacecraft capabilities. It begins by knowing what functions are needed in a smaller package. Once identified, these functions can be created by nanotechnology or mapped to an existing device that possesses low SWaP.

2.8 Summary

There are several experiments with spacecraft subsystems and payloads that are reducing the SWaP while delivering more performance. With this, advanced materials and microelectronics have allowed the reduction of the SWaP of the spacecraft bus and its components. The CubeSat presents the spacecraft developers with a standardized bus for testing these low SWaP subsystems and payloads for a low cost. If all of these efforts were synergized to support a process that employs them in an operation scenario, then more benefits could be gained. That is, take these experiments to the next phase in the evolution of smallsats and their components, an operational mission. Considering the budget and schedule challenges the space acquisition is currently experiencing, these advancements present the space community (commercial and government) with alternatives to the old way of doing business.

There is no traceability back to the original capability, i.e. spacecraft bus, subsystem, or payload. There are advocates for smaller and simpler spacecraft [11]. Advocates for small satellites have no process to connect the advanced technology to the

capabilities that exist on large satellites. This process is needed if the small satellites are to move experimental missions to an operational mission. The next section will discuss a process that studies the capabilities of large satellites and maps selected capabilities to the low SWaP sensors being advanced through experimentation. The process is called satellite capabilities mapping.

3. Methodology

3.1 Overview

The utility of small satellites is maturing and provides usefulness in some mission areas. Space weather is the most popular application at this time. The smallsat utility is increasing because of the interest from several members of the space community and the large number of active experiments. These experiments are evolving the CubeSat bus subsystems and payloads. As the experiments continue to advance the capability of the subsystems for the standardized CubeSat bus, developers will eventually have a marketplace of standard subsystem components. This will assist in shortening the development cycle of the CubeSat bus for specific missions. The CubeSat payloads will follow this trend but never completely loose the unique and specialized aspects introduced by any specific mission. Nonetheless, both will benefit from the evolution being led by these experiments.

As capabilities are reduced in size, weight, and power for the CubeSat bus, the original motivation for evolving a specific capability is not being captured, documented, nor utilized. The experiments above are only that, experiments. None of the researched experiments discuss any intent to move to an operational mission, even if only as a supplement to another system. There are capabilities lost, e.g. those illustrated by the SESS, during spacecraft acquisitions due to budget cuts, schedules overruns, or for many other reasons with no method to replicate or obtain those capabilities on another platform. When capabilities are lost, the solution is to use legacy sensors, equipment, or satellites [11]. The cost and time (schedule) involved in pursuing this approach or method sometimes gets the original program back on schedule but with old technology and

typically fewer capabilities [1]. The NPOESS solution is to employ the Space Environmental Monitor (SEM-N) which only provides data for five of the original thirteen EDRs and only one of the five fully meets requirements [5]. In the end, there are eight capabilities not delivered. If those eight capabilities were needed, the developers would continue to employ the same mindset, i.e. large sensor, medium to large satellite, and several years of development.

The space community, especially developers, would benefit from having a tool that assists with developing small solutions to lost (large-scale) capabilities. The tool or process would aim to keep the newer technology or capability moving forward. The (mapping) process would serve as this tool by mapping lost capabilities to low SWaP sensors that could be integrated onto a CubeSat. Square pegs do not fit into round holes; however, if the square peg can be separated into pieces, then each individual piece can be moved through the hole one at a time. Similarly, if the square peg capability can be performed by a group of smaller pieces, then replace the peg and perform the mission with the smaller group. In the real world, this would be attempting to integrate large-scale, large satellite capabilities to a CubeSat. The challenge is determining if those capabilities can be separated into their basic components or if they can be mapped to a low SWaP sensor, even if experimental, to fly on its very own small satellite or CubeSat. The process introduced below will perform the task of mapping capabilities from large satellites to smaller ones like CubeSats. Currently, no such process exists. Typically, as evident in the NPOESS dilemma, when a large-scale capability is lost the developers rush to utilize existing, or old, instruments without examining the advancements of smallsat

experiments. As will be seen in the space weather mission area, there are small (low SWaP) sensors that can provide needed capabilities.

The capabilities mapping process is limited to spacecraft subsystems and payloads. The orbital parameters will be considered outside of the scope of the mapping process for two reasons. First, the original capability will have its own orbital parameters established in its requirements. The mapping process sees no need to change these parameters since the stakeholders and developers confirmed them. The second reason is that launch availability, cost, etc. in an area under study by many offices and organizations. The solution presented by the mapping process will either follow the original orbital parameters (i.e. exact launch defined) or pursue a shared ride (i.e. accept any launch offered).

3.2 The Semantics and Attributes of Capabilities Mapping

The term mapping refers to the process of copying or replicating a (operational) capability from its original form to a different form. The goal of the capabilities mapping process is to analyze the large-scale satellite capability, decompose the capability to its basic function(s), and map those functions to a low SWaP sensor compatible with a smaller platform, i.e. the CubeSat. The term capability can refer to that of a satellite subsystem or payload. "A capability is the ability to achieve a desired effect under specified standards and conditions through combinations of ways and means to perform a set of tasks. [7]" The capability achieves its effect by performing specific functions, i.e. an intended task, activity, or purpose [25]. There are a few attributes in these definitions that assist in understanding and mapping the capability. The desired effect coming from the capability is the output that is expected by the user. This

deliverable may be thought of as raw data, data computed by a software model, a report produced by an analyst interpreting the data, or an automated response to an adverse event. Since all three occur after the sensor has performed its function, they will all be considered one deliverable. They process the data whether it comes from the legacy sensor or a low SWaP experimental sensor. The deliverable enables the user to accomplish a mission so it is an important attribute of the capability.

A capability is typically contained within some type of physical hardware that contains the components that perform these functions for the capability. An instrument is a device for measuring the present value of a quantity under observation while the sensor is the mechanical device that is sensitive to light, temperature, radiation level, or the like, that transmits a signal to the measuring or control instrument [26]. Regardless of the size of the satellite's subsystem or payload, the capability mapping process decomposes the components, instruments, and/or sensors to identify and separate their basic functions, i.e. the function that performs one task only. Each individual function can then mapped to a low SWaP CubeSat compatible sensor that performs the same function(s).

The system's technical requirements document (TRD) contains the original needs for the subsystems and payloads. Among those requirements is a specific requirement for the capability of interest. The specific requirement is the second attribute that should be noted, understood, and documented for the process. It offers a significant advantage to capabilities mapping process. The requirements analysis process is arduous for space systems acquisitions. Therefore, once approved by stakeholders, utilize the requirements instead of repeating the painstaking process of developing new requirements for a smallsat solution or alternative. "The steps to write the requirements take too long.

Recently, there are more processes being added into acquisition programs. If it takes us years to get through a requirements process that gets you to the beginning of the program, something is wrong with the process. [3]" Don't reinvent the wheel because an approved set of requirements will have defined thresholds and objectives. In addition, the ground element, mission operations, and the command, control, and communications architecture have already planned [21]. Thus, as the capability is mapped, the criteria (metrics) the new system must meet has already been established. One goal of the capabilities mapping process is to utilize all the information and technical data developed and agreed upon by stakeholders. This avoids returning to the requirements development phase and instead starts at the decomposition and definition phase. The metrics defined by the original requirements (thresholds and objectives) and deliverable will create the measure of effectiveness (MOE), measure of performance (MOP), and measure of suitability (MOS) for the new system. Whether this system is a single CubeSat or constellation, the MOP and MOS apply numerical data to the analysis which provides the developer, stakeholder, and ultimately the user a level of confidence. If the selected sensors or proposed system cannot meet these metrics, they still provide the quantitative data to determine a performance level that is good enough. Utilizing the investment already put forth in the development of requirements and mission architecture, standardized equipment such as the CubeSat bus, and advanced low SWaP technology resulting from numerous experiments, the capabilities mapping process will reduce costs, shorten the schedule, and allow developers to focus on the satellite subsystems and/or payload sensors.

3.3 The Capabilities Mapping Process

The capabilities mapping process once one or more capabilities of interest are identified to be performed on a CubeSat. The system that contains the capability will undergo system and requirements decomposition, both starting at the system level. While the capabilities mapping process can be applied to a subsystem or payload, the focus here will be on payload capabilities. The capability chosen for mapping will be referred to as the capability(ies) of interest and can be selected at different levels, e.g. an entire payload, an instrument, or a sensor. Regardless of level selected, the process starts with a system and requirements decomposition with the intent to determine the most basic function typically found in the sensor and its corresponding requirement (Figure 17). Once the individual sensors are identified, three sensor attributes are defined (Table 7)

Table 7. Sensor Attributes

ATTRIBUTE	DEFINITION
Requirement	QUESTION: What is the user need for this sensor? Requirements are defined by a user need that relates the action to be performed by a sensor, instrument, or the like to the user’s expected output. They are typically measureable, testable, and are detailed enough to assist the original design.
Deliverable	QUESTION: What is expected from this sensor? A deliverable is a tangible or intangible object produced as a result of the capability that is expected by the customer.
Capability	QUESTION: What does the sensor have the ability to do? The ability to achieve a desired effect through a combination of ways and means to perform a set of tasks.

and the system decomposition transitions to a functional decomposition. The mapping process proceeds with the functional decomposition which establishes three attributes for the sensor: requirement, deliverable, and capability.

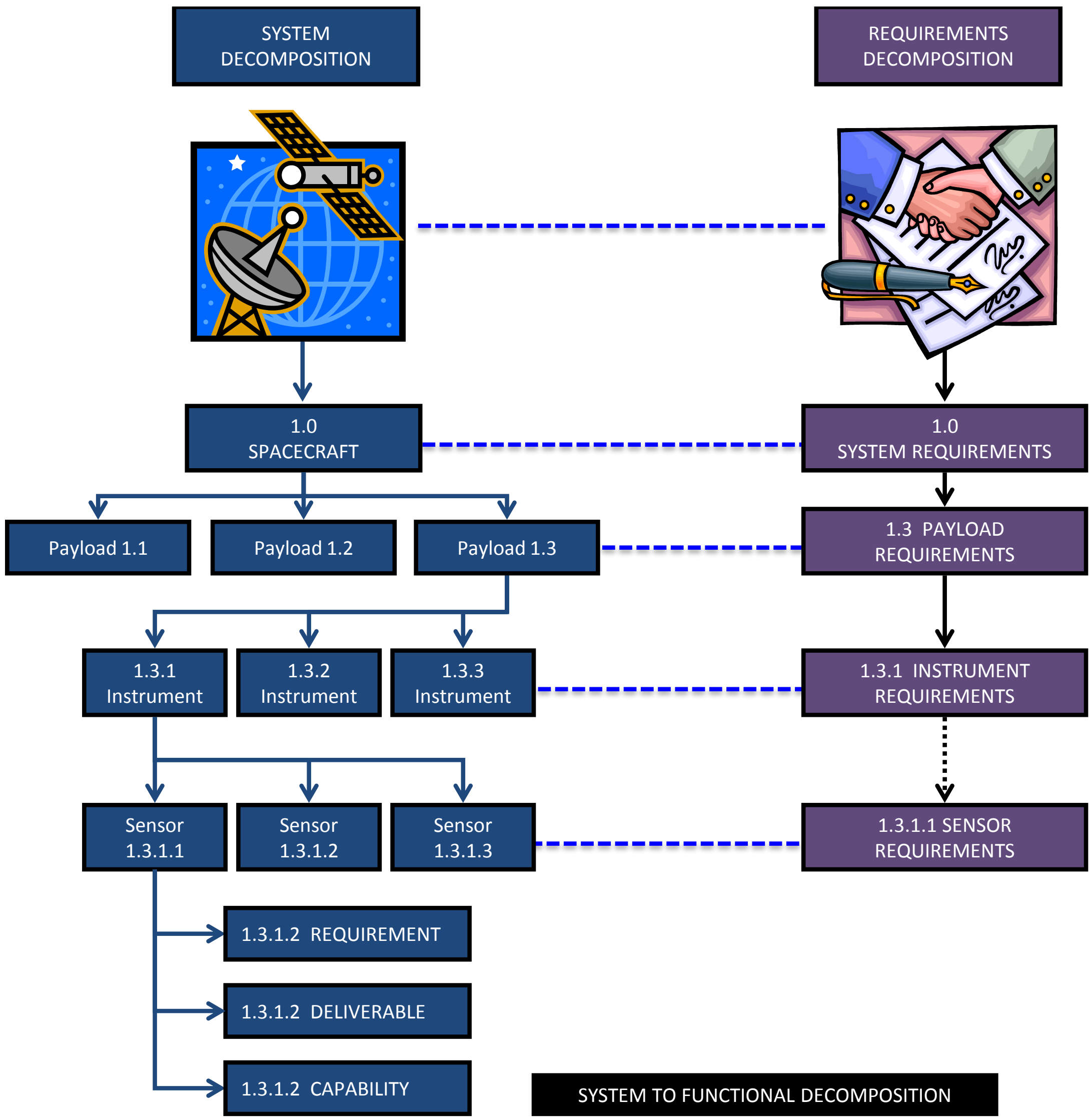


Figure 17. System and Requirements Decomposition

The functional decomposition is applied to one or more sensors and defines the sensor's capability attribute by decomposing all of the independent functions it performs (Figure 18). The sensor's capability comes from its ability to perform the functions separated by the functional decomposition. A function is defined as performing one task only. The system and functional decompositions performed in sequence take a complete system, identify a specific capability of interest performed by the system, and decomposes the relevant components (payload, instrument, and sensor) until the basic functions of that capability are identified, isolated, defined, and understood. As shown in Figure 18, sensor 1.3.1.2 performs three functions, 1.3.1.2.1-3. These three functions will be the subject of the capabilities mapping process to seek a low SWaP equivalent. This will be shown after the function's metrics are defined which is discussed next.

The requirements decomposition isolates the specific requirement(s) that will be used to define the requirement attribute which shows the sensor (1.3.1.2) to requirement (1.3.1.2) relationship (Figure 18). This begins by examining the system requirements that define the spacecraft and its payloads. The requirements for the payload that provides the capability of interest will also define the requirements for all of the instruments and its sensors. The requirement for the sensor isolated by the system decomposition, e.g. 1.3.1.2 in Figure 18, will provide an explanation of what the sensor must accomplish along with quantitative performance specifications such as thresholds and objectives. The lowest level requirement definition may only define the instrument which would then apply to inclusive sensors. Next, the deliverable attribute is defined by the intangible (or tangible) output expected by the user. Both will play a role in defining the metrics that

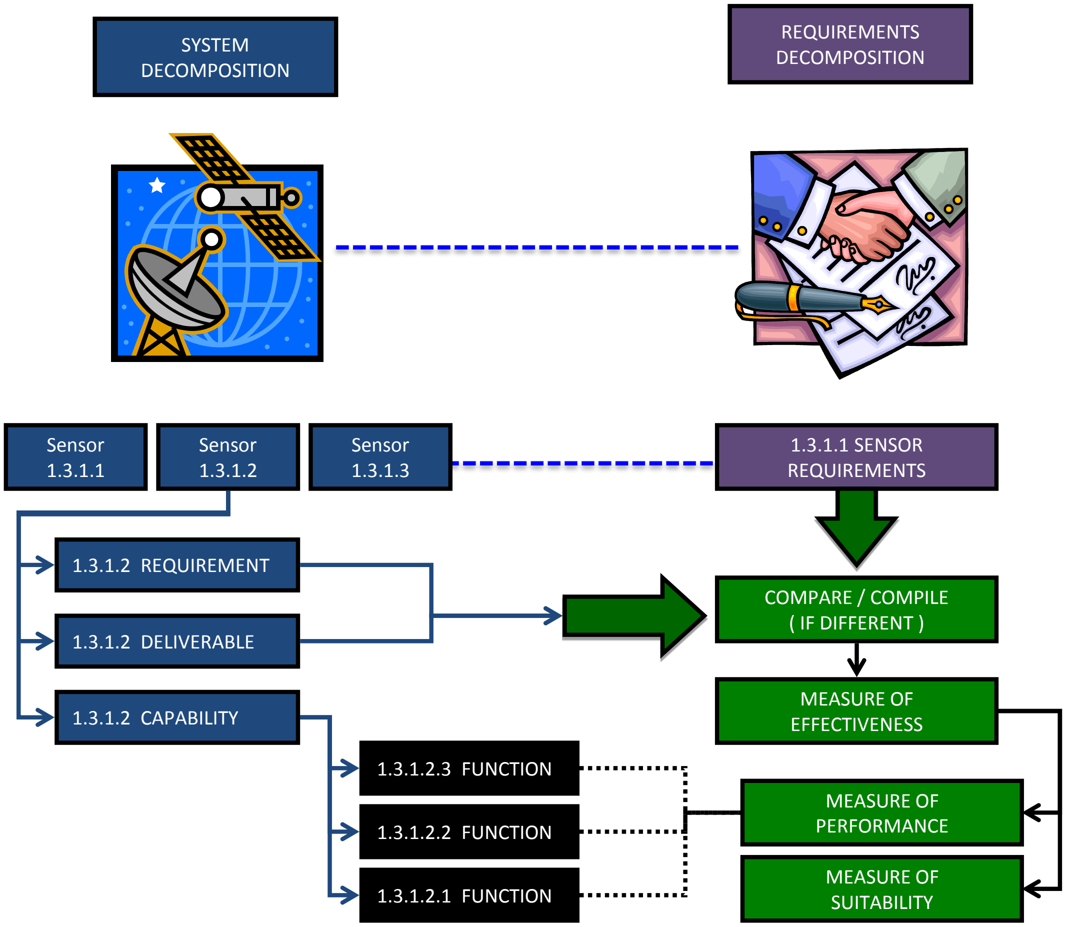


Figure 18. Functional Decomposition and Metrics Definition.

will be used to verify, validate, and approve the selected sensor(s) after the mapping process. The sensor's requirement and deliverable attributes may be the same for some systems; however, if not, they are compared and combined into a set of metrics.

These metrics (comprised of the original requirements and deliverable(s) data) will be contained in a MOE, MOP, and MOS, defined in Table 8. The MOE will relate quantitative factors such as performance, effectiveness, and suitability to the functions identified and separated by the functional decomposition of the capability attribute. This applies quantitative performance specifications to the functions of the original capability.

Table 8. Metric Definitions [7]

METRIC	DEFINITION
Measure of Effectiveness (MOE)	A measure designed to correspond to accomplishment of mission objectives and achievement of desired results. Several MOPs and/or MOS may be related to the achievement of a particular MOE.
Measure of Performance (MOP)	Measure of a system's performance expressed as speed, payload, range, time on station, frequency, or other distinctly quantifiable performance features.
Measure of Suitability (MOS)	Measure of an item's ability to be supported in its intended operational environment. MOS typically relate to readiness or operational availability, and hence reliability, maintainability, and the item's support structure.

Therefore, the system, functional, and requirements decomposition has identified what functions the sensor performs to provide the capability as well as a MOE defining the expected performance of those functions. The MOE will be employed later in the process to determine if a low SWaP sensor can meet the original requirements and user expectations. Any low SWaP sensor function that is mapped to the function of the original sensor will be analyzed and evaluated according to the MOE. Thus, if the sensor meets these metrics, it meets the expectations of the original sensor, or instrument.

There are numerous low SWaP sensors are being developed in experimental spacecraft; therefore, obtaining a list of compatible and available sensors will require extensive research. For the purposes of the mapping process, all sensors regardless of technology readiness level (TRL) will be considered eligible. Since the bus of choice has been determined to be the CubeSat, establishing eligibility criteria for any application is simple due to the standardized characteristics of the CubeSat discussed earlier. This illustrates the advantage of the CubeSat bus as well as demonstrates how the

development cycle is shortened. Therefore, the entry criteria for low SWaP sensors will be defined by CubeSat standards [28]. This criterion would be defined differently if a different bus were used or specifically designed. Once the low SWaP sensors are selected for consideration, a functional decomposition will be performed so all their functions can be viewed, analyzed, and considered individually.

With the individual functions listed for both original capability and low SWaP capabilities, the next step is to map them to like functions. This process may produce different combinations of sensor to function relationships. For example, a low SWaP sensor may perform more functions than the sensor it maps to and vice versa. Functions may be mapped to other functions directly or indirectly as shown in Table 9. A simple indirect capability mapping example could be a sensor that collects data regarding the displacement and time for a moving object. If the function desired was velocity, it could be calculated using the object's displacement and change in time.

If there is no low SWaP sensor that possesses a function that can be mapped to the function of the original sensor, whether directly or indirectly, then the mapping process

Table 9. Types of Capability Mapping.

TYPE	DESCRIPTION
Direct Capability Mapping	The capability being mapped and the sensor being considered perform the exact same function, e.g. both detect the same phenomena.
Indirect Capability Mapping	The original capability is accomplished via a mathematical relationship between the phenomena detected/measured and the phenomena needed. Original Capability: measure velocity Low SWaP Capability: measures displacement / time, therefore, velocity obtained via $V = \Delta d / \Delta t$

has identified a potential area of research and development (R&D). This means that if the unmapped functions of the capability are needed then the design specifications for those functions have been compiled into the MOE. Therefore, from the MOE, developers can determine if an existing sensor can be modified, a new sensor needs to be developed, or if the functionality is simply impossible to accomplish in a low SWaP scale/package. Finding an answer to these questions is an R&D project by itself but would guide the development or save time and funding by confirming what is and is not possible.

The low SWaP sensor's has its own performance specifications with uncertainty which allows a MOE to be defined. The sensor's MOE will play an important role in the decision process. Every low SWaP sensor must meet a defined minimum level of performance and specify any limitations to its support structure. The MOE from the original sensor will serve as the starting point. In regards to the MOP, if the low SWaP sensor can meet the original sensor's threshold (original MOP) then the sensor is deemed functionally acceptable. If the low SWaP sensor cannot meet the MOP required by the original capability, then an analysis of what is good enough is needed. The concept of good enough was discussed earlier and would require stakeholders and developers to make a trade between: cost, schedule, performance, and possibly other characteristics. The decision would require defining a good enough acceptance level which could be specified as a percentage of the original, e.g. an 80% may be acceptable due to the quicker schedule and lower cost. The decision could also be easy to make if having some capability was better than none at all. As an example, return to the determination of an object's velocity, first defining or noting the sensor's uncertainty. Suppose a low SWaP sensor with the functionality to measure displacement and time had the following

uncertainties: displacement sensor: ±20% and time sensor; ±15%. The uncertainty of the velocity (i.e. desired function) after computation would be ±35%. If the original sensor had an uncertainty of ±10% then the low SWaP sensor would not meet the MOP. However, if stakeholders and developers deemed the ±35% uncertainty good enough then the low SWaP sensor would be accepted. If the low SWaP sensor could not meet the good enough level of the MOP, then once again an area of R&D has been revealed. If any of the functions are not met and deemed essential then developers know exactly where to start and have quantitative data as a starting point. Thus, even if a sensor (with needed functions) is not available or cannot meet the defined good enough MOP level, the mapping process is not a wasted effort.

The MOS is also part of the MOE. It identifies any factor that must be met in order for a low SWaP sensor to operate in the intended environment. This would include any requirements of specific orbital parameters, specific communication with a neighboring satellite, or any other factor that would hinder the expected performance. Therefore, as the requirements are decomposed from the system level down to sensor level any characteristic related to the function and/or performance must be captured in the MOS. This would be found earlier that the sensor level requirements either at the system/spacecraft or payload requirements. For example, if a sensor relied on data from a second sensor (which then includes communication) in a different location to perform a computation prior to downloading data, then any requirements that specify the distance, altitude, orbit, inclination or any other parameter must be captured in the MOS. The integration of the sensor into the CubeSat is a process that is common among all spacecraft development, and therefore discussed briefly. The integration process

determines the number of sensors and CubeSats that will be required to meet the threshold performance level of the mission as defined by the original requirements. The exact number of CubeSats will depend on two factors. First, the SWaP of each sensor will determine how many will physically fit into the bus. Second, the coverage will determine the quantity of CubeSats required in the final constellation.

3.4 Summary

The capabilities mapping process is a synergistic method that utilizes the successful experimentation of low SWaP sensors, exploits the standardization of the CubeSat bus, enables decision makers with quantitative data to determine what is good enough, and specifies the functionality to be developed by the R&D community. There are many mission areas the process could be applied but the popularity of experimental space weather sensor makes it the best choice for application. The capabilities mapping process will be applied to the SESS that was de-manifested from the NPOESS program.

4. Analysis, and Results

4.1 Overview

The capabilities mapping process separates a system into its basic functions so those functions can be mapped to low SWaP sensors that perform the same functions or produce the same products. This presents stakeholders and developers with a tool to begin the development of a small satellite capable of doing the mission of a large spacecraft. The data (metrics) obtained from the process also enables developers to determine if the low SWaP sensor will meet the threshold of the original sensor and if not, then what is good enough for the mission. If neither of these is satisfied, then the data obtained would provide specific guidance for additional R&D efforts. The knowledge gained from the mapping process is discussed below as well as what next steps would benefit the process and the space community.

Space weather has already been identified as the best application for smallsats and the popular among academic experiments. Therefore, since there is a significant space weather monitoring gap following the problems of the NPOESS program, the best application of the capabilities mapping process would be to selected sensors on the SESS no longer included. If successful, it will link the academic experimental space weather projects to an actual operational mission and provide developers with a process framework to evolve. The application that follows attempts to make the square peg fit into the round hole.

4.2 Application of the Capabilities Mapping Process

The de-manifested SESS was intended to collect and provide data for selected space environmental parameters. Once relayed to the ground stations, the data would

have been ingested into a modeling system that analyzes the data and produces an EDR. The loss of the SESS will leave the United States with either lost or severely degraded capabilities as shown in a previous section. As discussed above and shown in Table 6, the SESS contains five instruments. Of these five instruments, the capabilities mapping process will be demonstrated on the Thermal Particle Sensor (TPS) to determine if its capabilities can be mapped to a set of low SWaP sensors capable of monitoring the required space weather phenomena. The TPS is a set of plasma collectors used to measure and characterize the densities, temperature, and drifts of the thermal ionospheric plasma at satellite altitude [5]. It is the primary provider of data for three EDRs as shown in Figure 8 above. The Initial Operating Requirements Document (IORD II) for the NPOESS space environment monitoring mission was revalidated in 2006 by the Joint Requirements Oversight Council (JROC) and have not changed [11]. These requirements and the EDRs (deliverable) will define the metrics by which the selected low SWaP sensors will be verified and validated.

The TPS is identified as the capability of interest and therefore will undergo a system, functional, and requirements decomposition. The TPS capabilities mapping process will treat the TPS as an instrument comprised of four sensors. Therefore, the TPS capabilities mapping goal is to identify and isolate all functions of the TPS instrument and map those to like functions performed by a low SWaP, CubeSat compatible sensor. There will be no other capabilities included in the TPS capabilities mapping process; however, if a selected sensor has the capability to detect different phenomena in addition to that required, then those capabilities will be referred to as secondary and considered for use as long as they do not interfere with the TPS

capabilities mapping. An analysis of the MOE for the TPS instrument capability and the selected low SWaP capability will support the final decision.

System and Requirements Decomposition

With the capability of interest identified, the capabilities mapping process starts by performing the system and requirements decomposition as shown in Figure 19.

The requirements decomposition allows the TPS sensor requirements to be separated from top level system requirements. Caution must be taken not to overlook any requirements that pertain to the ability of the sensor to perform its functions in the intended environment specified by the system, spacecraft, or payload requirement, e.g. proximity of another sensor, spacecraft, etc. These requirements must be carried through the requirements decomposition and recorded during the development of the MOEs. The requirements decomposition examines the Integrated Operational Requirements Document (IORD-II) and concludes with sensor requirements 4.1.6.7.4, 4.1.6.7.7, and 4.1.6.7.8 as shown in Figure 19.

The system decomposition starts with the system (i.e. spacecraft, ground stations, relay satellites, etc.), separates the spacecraft, and continues with the payload and instruments. The system decomposition ultimately identifies all sensors and isolates the specific sensor that performs the capability of interest. The TPS instrument shown as 1.1.1 in Figure 19 is accomplished by the functions performed by four sensors: Plasma Drift Meter, Faraday Cup / Retarding Potential Analyzer, and Langmuir Probe. Since the TPS performs the capability of interest, these four sensors will be functionally decomposed.

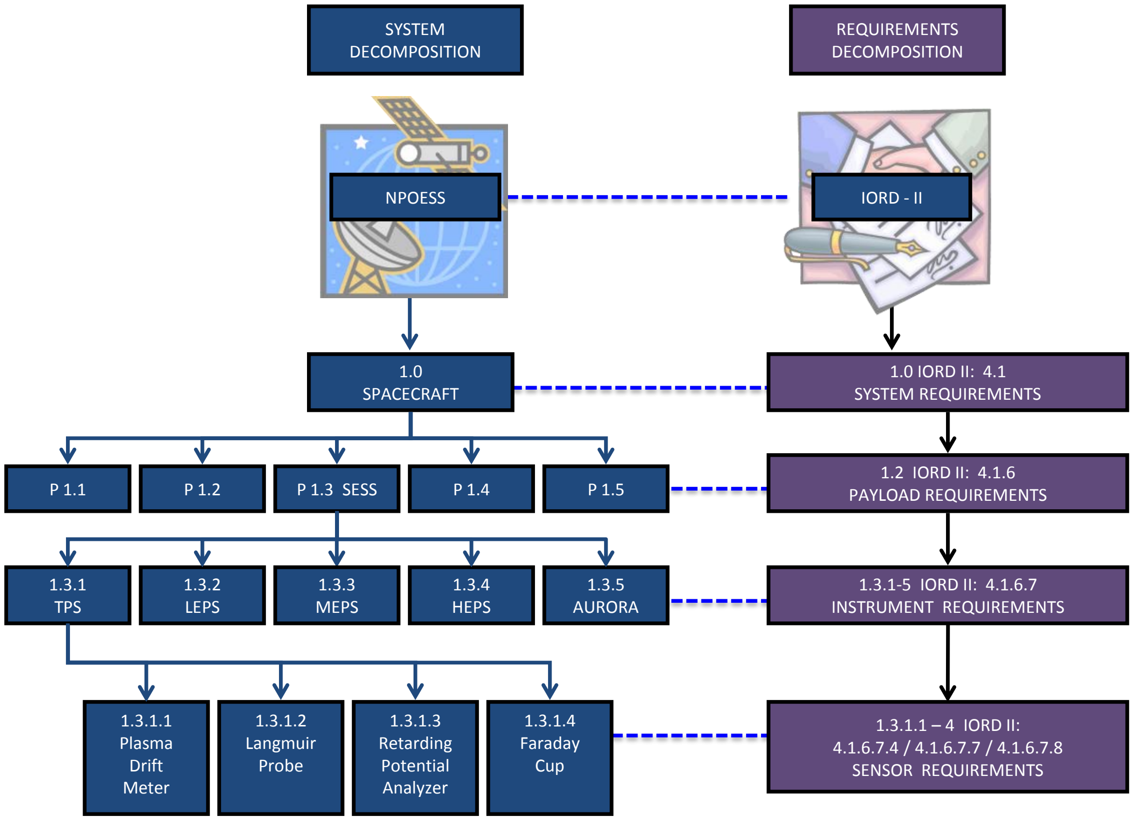


Figure 19. System and Requirements Decomposition.

Functional Decomposition

The functional decomposition begins by identifying the three attributes (requirements, deliverable, and capability) for each sensor as shown in Figure 20. The requirement and deliverable attribute are assigned five digit prefixes that correspond to the specific sensor. The IORD-II defines the requirement and deliverable for each sensor by three EDRs produced using data from these sensors. These EDRs are the Electric Field, In-situ Plasma Temperatures, and In-situ Plasma Fluctuations EDRs [5]. Therefore, the requirements for the delivered EDR (i.e. thresholds/objectives) will define the two attributes, requirement and deliverable. The capability attribute is defined by performing the functional decomposition and identifying all functions performed by each

sensor. As shown in Figure 20, there are a total of eight functions performed by the four TPS sensors. The separation of these functions allows them to be examined one by one. Figure 20 color codes the functions to show which EDR they support. These functions will be mapped after their metrics have been defined and low SWaP candidate sensors identified.

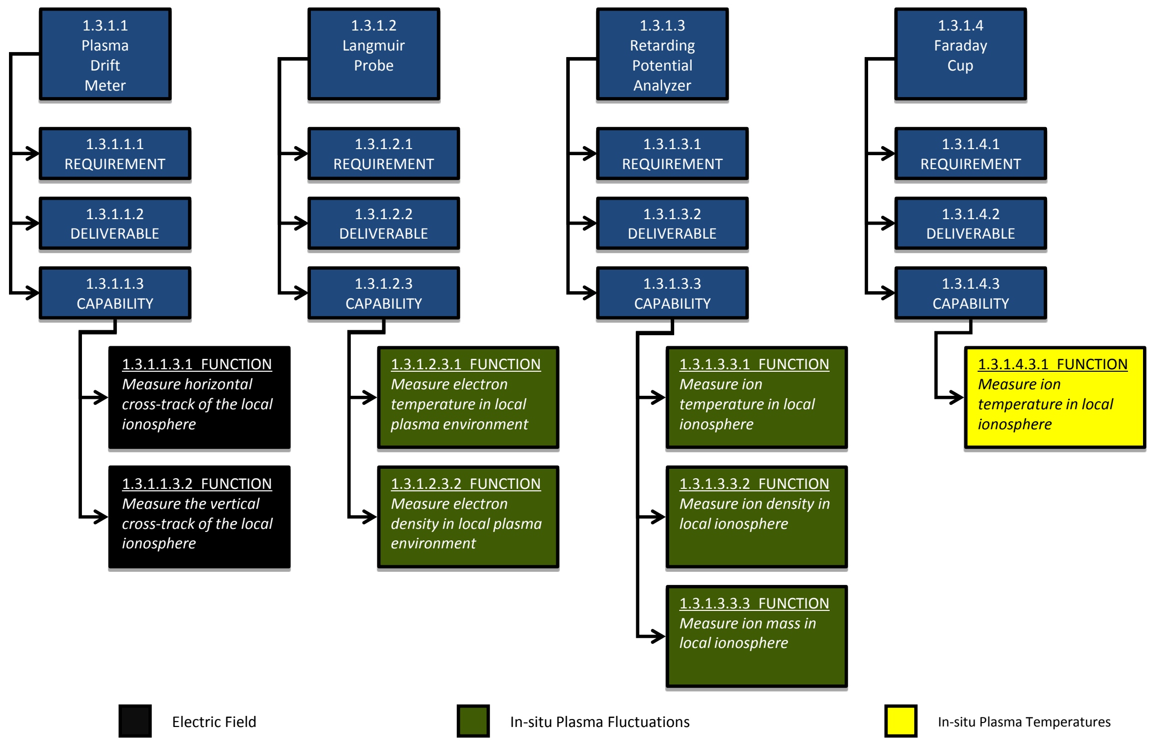


Figure 20. TPS Functional Decomposition

Metrics

Mapping the functions identified is only part of the mapping process. These functions need metrics in order to know whether the low SWaP sensor can perform the mission. The completion of the system, functional, and requirements decomposition provides the information needed to establish the MOE for the capability, i.e. sensor functions. Since the requirement and deliverable are defined by the EDR, the need to

compare and combine these attributes into a MOE is not needed. The MOEs for the TPS will be defined by the threshold and objectives for the Electric Field, In-situ Plasma Temperature, and In-situ Plasma Fluctuations EDRs (Table 10). The formulation of these MOEs and how they relate the quantitative metric to function are shown graphically in Appendix A.

Low SWaP Sensor Selection Criteria

Since there are few spacecraft components, especially low SWaP sensors, available as commercial off the shelf (COTS), research and inquiries will have to be done with industry and academia. The search for these sensors will require some selection criteria. The standardized CubeSat bus simplifies the establishment of selection criteria by providing the CubeSat Design Specifications Document [28] published by Cal Poly.

Table 10. TPS Metrics - Defined by Environmental Data Records [29]

EDR (TPS Metrics)	Sensor MOEs per EDR
Electric Field *An in-situ measure of the ambient electric field.*	MOP: - Measurement Range: 0 to ±150 mV/m - Horizontal Cell Size: 10 km - Horizontal Reporting Interval: 10 km - Measurement Uncertainty: 3.0 mV/m
In-situ Plasma Fluctuations *In-situ measurement of plasma density fluctuations.*	MOP: - Measurement range: -- Mean Plasma Density: $5x10^3$ to $5x10^6$ cm^{-3} -- Fluctuation Scale Length: 5 to 10^4 m -- Spectral Index: 1 to 5 -- δn / n - Measurement Uncertainty: -- Mean Plasma Density: 20%
In-situ Plasma Temperatures *In-situ measurements of the electron and ion temperatures.*	MOP: - Measurement range: 500-10,000 K - Measurement Uncertainty: 10%

These specifications expedite the development of the bus. The available sizes of the CubeSat were discussed above in chapter two. In regards to the subsystem and payload, establishing SWaP criteria for selecting low SWaP sensors can only be accomplished by considering the various CubeSat sizes (e.g. 1U, 2U, 3U, etc.) which limits the solar panel sizes thus having an impact on the batteries. The low SWaP sensors will have to be selected first in order for the developers to determine the true overall SWaP. Therefore the integration of each low SWaP sensor into a properly sized payload will require an analysis involving power, mass, and volume once selected.

Four sensors were considered for the TPS capabilities mapping process and are listed with a description of their functions in Appendix A. These low SWaP sensors have an experimental status and their metrics may be based on lab test results. If a sensor has flown, then it should have on-orbit performance data to better define the MOE. The data, whether it is from a lab or on-orbit experiment, will be used to define the MOE. The WINCS sensor will be selected to demonstrate the process of defining an MOE for a low SWaP sensor. The other three sensors will be used only to illustrate a function-to-function mapping process.

WINCS simultaneously provides the full ion-drift vector, ion densities, and ion temperatures. These follow from the measured angular-energy distributions of the ion flux developed by the satellite velocity. The ion drift can be translated to deliver the data required by the Electric Field EDR. The electric field associated with plasma moving in a magnetic field is given by equation 1 where **E** is the electric field, **V** is the velocity, and **B** is the magnetic field [27]. Thus, WINCS can provide an in-situ measurement of the

$$\mathbf{E} = -\,\mathbf{V} \times \mathbf{B} \qquad 1.0$$

Table 11. **WINCS MOE (Electric field translated from ion drifts)**

EDR (WINCS)	Sensor MOE
Electric Field *An in-situ measurement.*	MOP (threshold): - Measurement Range: 0 to ±150 mV/m - Measurement Uncertainty: 3.0 mV/m

electric field using its functionality to measure the ion-drift vector and applying equation 1.0. The MOE for WINCS is given in Table 11.

Mapping

With the low SWaP MOE defined, the TPS mapping process continues by mapping the functions of the low SWaP sensors to the TPS sensor functions. As shown in Figure 21, the functions decomposed from the TPS sensors are listed on the left and the functions performed by each low SWaP sensor on the right. The functions of the TPS sensors are color coded to indicate which EDR they support. Similarily, the functions of the low SWaP sensors are color coded to indicate which sensor they come from. If the functions have been defined and described in like terms then the mapping process looks for matching descriptions. For example, the TPS function 1.1.1.3.3.2, measure ion density in local ionosphere, maps to the WINCS function described as measure ion density. The only difference is the location specified in the TPS function. It specifies the location as the local ionosphere which should also be in the system or payload requirements and recorded in the MOS. As they stand, these two functions are the same but in order for the WINCS to completely satisfy the original function an in-situ configuration with orbital parameters specified by the MOS will be required. As Figure 21 shows, all eight functions map to a function performed by one or more low SWaP

sensor. This only identifies like functions, the next step is to use the MOEs for matching functions and determine if the low SWaP sensor can perform as well as the original.

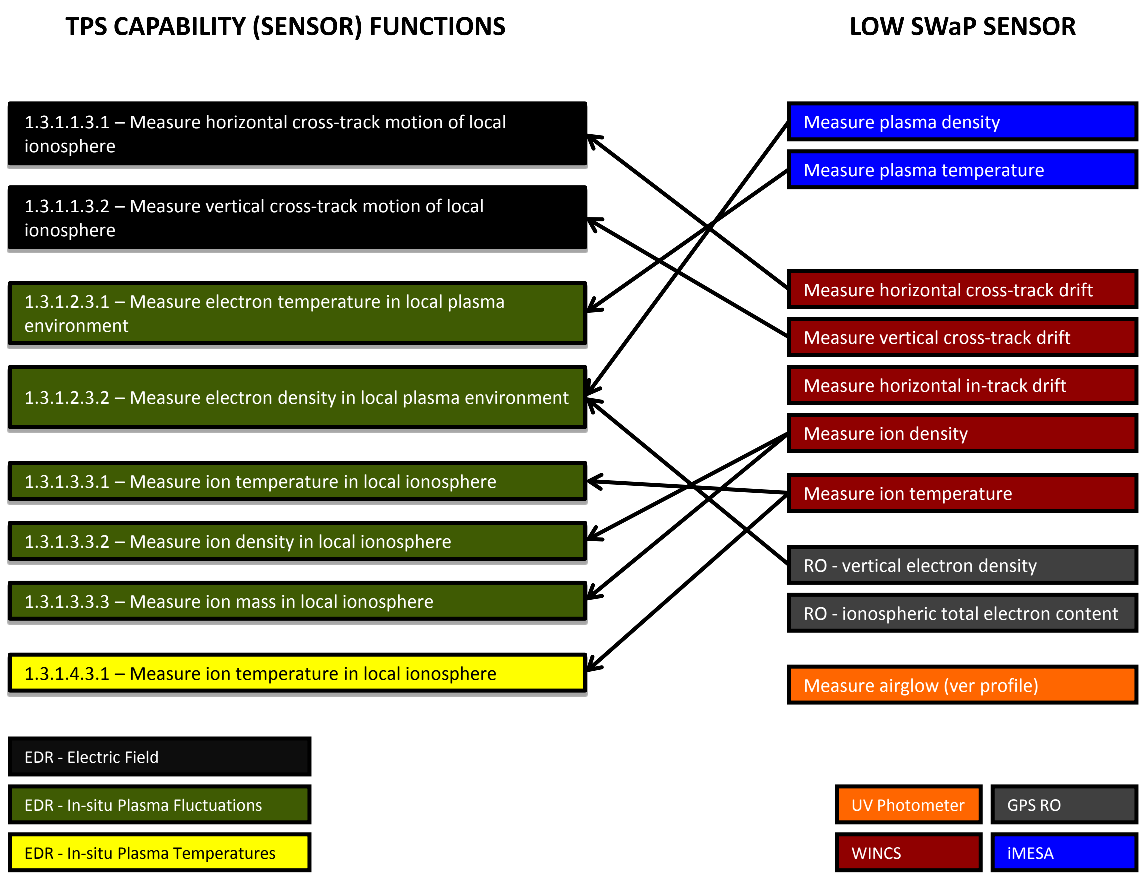


Figure 21. TPS Mapping Process

MOE Analysis

The analysis of the MOEs for mapped functions will be demonstrated by the two WINCS functions that map to the two functions supporting the Electric Field EDR. Figure 22 shows the analysis between the MOE of the TPS functions and the WINCS sensor. Examination of the WINCS sensor reveals that its measurement range and uncertainty meet the MOP required for the Electric Field EDR. This analysis is a confirmation that the WINCS functions can deliver the same performance as the TPS

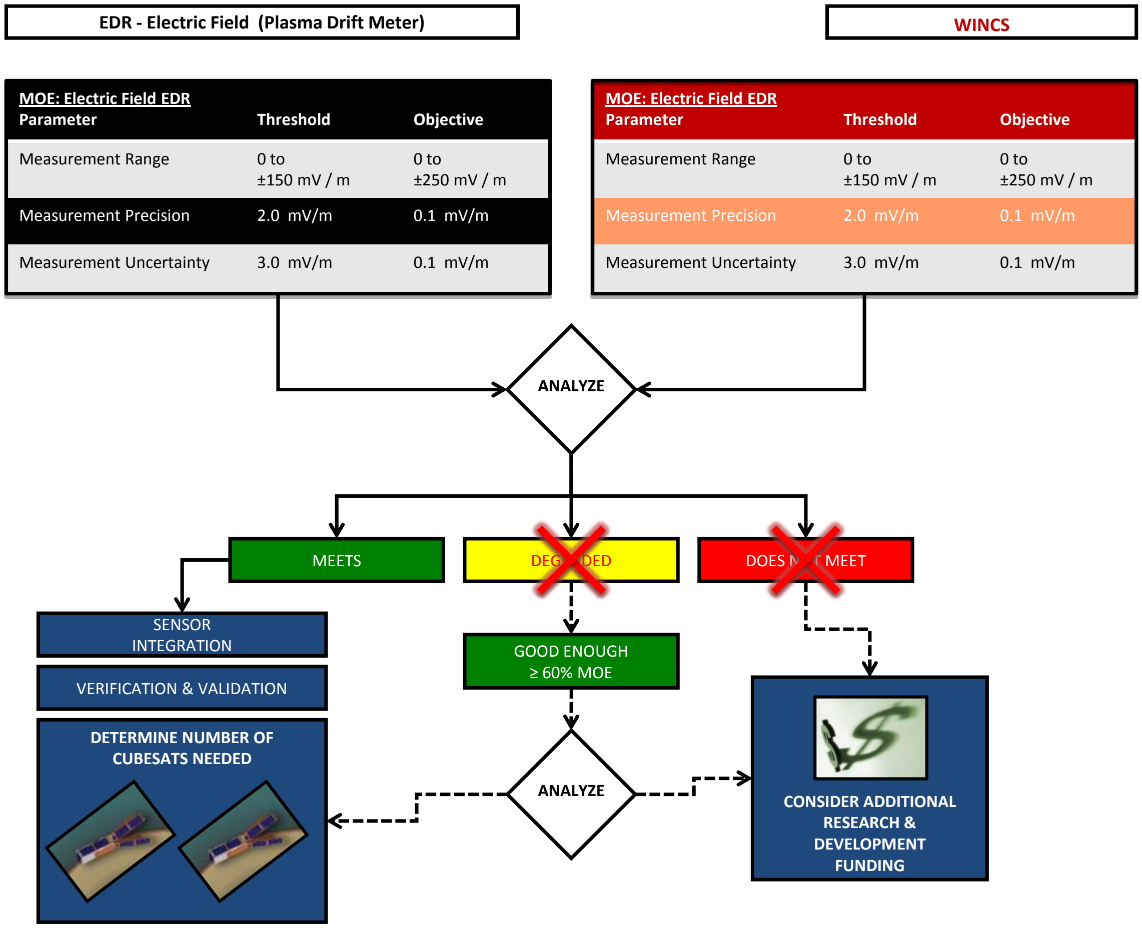


Figure 22. Measure of Effectiveness Analaysis

functions that currently support the Electric Field EDR. The MOS specifies that the Electric Field is to be monitored in the local ionosphere [29]. The advantages of the CubeSat is that it can be flown inexpensively in numerous orbits providing excellent global coverage that is difficult for larger systems to achieve. Not because of their performance but the cost of putting a large quantity of spacecraft in different orbits. Thus, these low SWaP sensors not only meet the original metrics but several advantages to global coverage. The conclusion is to integrate the sensors onto a CubeSat.The second involves meeting the threshold value of the MOE. As an example, suppose the WINCS measurement range for the electric field was ±120 mV/m. This performance would not

meet the threshold value and only deliver 80% of the TPS MOE. Therefore, stakeholders must decide if 80% is good enough, better than nothing (in this case), or should be recommended for additional R&D funding. Even when the capability mapping process doesn't reveal a complete solution or one that meets 100% of the MOEs, it enables stakeholders and developers with quantitative data to make decisions. In addition, it defines the exact area to apply this development, which requires funding.

4.3 Results

The WINCS and iMESA sensors perform the same functions as the original TPS sensors. The requirements of the original system that are captured by the MOE are key in determining the if these sensors can deliver the performance. The MOE offers developers a quantitative method of showing stakeholders low SWaP sensors are ready to compete with large-scale legacy payloads, instruments, or sensors.

The WINCS sensor represents a solution proposed by the capabilities mapping process. This solution can be supported by the quantitative data contained in and used by the MOE. In addition to meeting performance, Figure 20 shows WINCS contains the additional function of measuring the horizontal in-track drift which was not part of the original sensor. This demonstrates the increase in capability while reducing the SWaP. The SWaP for the TPS is proprietary information and could not be obtained but it is safe to say the TPS would not meet payload criteria for the CubeSat, thus making the low SWaP WINCS and iMESA sensors, a smaller, lighter, and less expensive payload to launch. The conclusion chapter will discuss the recommendation to expand the capabilities mapping process by studying additional functions, e.g. all five instruments on the SESS, and how these functions would perform on orbit.

The requirements decomposition led to the exact technical information needed to define the MOEs for the sensors functions. The objective and threshold supported the MOP while the orbital parameters and relationship with other components were contained in the MOS. The WINCS sensor met the threshold and objective which provides quantitative data to proceed. The requirements contain the technical information that describes what the system is expected and how well. The MOE applies this technical information to each applicable function so that the functions can be mapped as package. Thus, the function and its requirement can stand alone as a single entity. If any function were to be singled out for mapping or development purposes, all pertinent information would be readily available as opposed to just the function which provides any developer with a description of the sensor and how well it must perform. The developer benefits by identifying advanced sensors with the same functions. If that function does not exist, the function descriptions can be distributed to industry, academia, or lab that may be researching and developing the function in a low SWaP sensor.

The mapping process identifies two sensors that can deliver the data required for three EDRs, Electric Field, In-situ Plasma Fluctuations, and In-situ Plasma Temperature. The next step is to determine how well a CubeSat with the sensor identified by the mapping process will perform on-orbit.

4.4 Summary

The application of the capabilities mapping process to the TPS sensor successfully proves low SWaP sensors have potential if not operational capability. Space weather should be considered as a starting point. The more other capabilities and their functions are understood, via the system and functional decomposition, the better they

can be mapped to a low SWaP solution or defined for low SWaP R&D. The capabilities mapping process is the link between large-scale satellite capabilities and a smallsat solution. The next chapter will discuss the analysis and results from the capabilities mapping process.

The results from the application above support and suggest that the WINCS and iMESA sensors could perform the mission but there is more to be studied. The data provided by the MOE proves the functions can be performed but other factors must be considered. These factors are discussed in the next chapter.

5. Conclusions and Recommendation

5.1 Chapter Overview

The capabilities mapping process is the first step toward a repeatable process that utilizes CubeSats to perform missions of large satellites. As discussed below the process contributes by introducing a new paradigm to the status quo of spacecraft development. The process creates a framework for developers to work with and expand while maintaining stakeholder's confidence with the satisfaction of requirements.

5.2 Contribution to the Body of Knowledge

Through the process of the system and functional decomposition, the system can be viewed in terms of its most basic functions. As each of those parts are analyzed and mapped to a smaller equivalent, the power consumed, specific material used, and its mass can be reviewed and given the opportunity to be improved or replaced by one more efficient. The capability mapping process reveals the return (what the system is doing and delivering) on the investment (mass and power of the original system). The capabilities mapping process leads to a low SWaP set of sensors, as long as they exist, that makes integrating them into one, two, or more CubeSats more efficient. As research and development of low SWaP sensors and standardized CubeSat components continue, the number of low SWaP sensors available will increase thus presenting diverse capabilities (functions) for more mission areas. This will allow the process of mapping capabilities to be more expansive and expeditious.

In addition to the knowledge gained about the original spacecraft, the capabilities mapping process provides a new future for the dozens of experimental, low SWaP sensor within industry and academia. In fact, any spacecraft payload could be systematically

and functionally decomposed to its basic functions only to have the list of functions and MOEs released to industry and academia for development consideration. In this mode, the capabilities mapping process is guiding the marketplace of future low SWaP sensors. Add to this the standardized bus of the CubeSat and the development is even further simplified. Thus, the capabilities mapping process establishes the development criteria (by providing functions) and the CubeSat standards provides a standard bus and subsystems. All the developer has to do is build the sensor (capability) to meet the criteria and make sure it fits in a CubeSat bus. It is not quite that simple but the evolution and trend of small satellites in general is moving in that direction.

5.3 Benefits of Capabilities Mapping

There a several benefits of having a process that maps large-scale capabilities to small satellites. Aside from those presented by challenges like NPOESS, the capabilites mapping process present the opportunity to map almost any capability from a large satellite.

The process produces quantitative data that stakeholders can use to make decisions. If a user needed only a few of the capabilities contained on a spacecraft and in a different orbit, the capabilities mapping process could decompose the specific capabilities of that system and identify the exact functions needed, if low SWaP sensors with those same functions existed (via direct or indirect mapping), and if the CubeSat bus could be the solution to that user’s needs. Once again, if the low SWaP sensors do not exist, the specific functions with quantitative metrics are available to provide to developers (industry, academia) eager to take the challenge of developing a low SWaP sensor.

Resources are utilized and not wasted nor recreated. As shown in the requirements decomposition, the requirements that may have taken a year or more to create and approve are reused to create metrics that will evaluate a selected low SWaP sensor. Also, if no low SWaP sensor (function) exists, the reused requirements can be applied to an advertisement distributed to industry or academia to develop the sensor.

CubeSats have been used almost exclusively to perform on orbit technology demonstrations. Those demonstrations represent technology that could serve an operational mission. The capabilities mapping process is a link not only between large and small capabilities, but also experimental to operational.

Lastly, the risk is low when employing the capabilities mapping process. The sensors may be experimental but that alone consumes a lot risk. If the experimentation was not successful then it would not be considered a candidate low SWaP sensor. But if the experiment were successful and hence overcame the risks, then integrating it as a replacement for a large-scale capability brings little risk. At the same time, the technology can be refreshed more frequently allowing the lower TRL level sensors to mature. For example, during a three year mission, the sensor being flown could be advanced, its functions studied and documented, and provide guidance and lessons learned for future sensors.

5.4 The Future of Capabilities Mapping

Since space weather is strongly recommended as an excellent mission area, the data collected by WINCS and iMESA sensors should be ingested into the current models used by DMSP. This would not only validate their performance but also the capabilities mapping process. The need for a process such as that developed in this thesis is certainly

needed since smaller satellites are getting more interest, budgets continue to shrink, and user needs change for frequently. Consider a database of CubeSats that deliver one, two, or more capabilities that could be developed and put in orbit in 12 months. The CubeSats in this database could be the result of the capabilities mapping process. That is, as capabilities of interest are selected and found to have an acceptable low SWaP equivalent, the solution should go into the database for other users. There is clearly a future for the capabilities mapping process. The process instroduced in this thesis is only the foundation for a larger framework. The capabilities mapping process would benefit from additional research that would take the individual CubeSat with their low SWaP payload and predict its success on orbit. Since the MOS records all system, spacecraft, and payload requirements during the system and requirements decomposition, it provides the information to develop a model and simulation of one CubeSat or a constellation for various orbital parameters. A simulation would allow the CubeSat to be integrated, tested, and evaluated as part of a larger network that determines the optimum number of CubeSats to fly. It would also support a mission concept to illustrate data rates, autonomous operations, or other system parameters that make up the CONOPs. This information could be used to propose the CubeSat solution to government program offices or commercial companies. If all requirement data is captured by the MOE and used to define the simulation, the risks, trades, and limitation could be better understood.

Thus, the ability to map large-scale capabilities to a constellation of CubeSats would mark a significant milestone in the utilization of small satellites. Most importantly, the quantitative data brought through the full process of mapping capabilities to simulating a constellation on orbit would validate the solution to stakeholders.

5.5 Conclusion

The capabilities mapping process is a logical procedure that improves the understanding of the original sensor and the system by analyzing the functional relationships among the requirements. It utilizes the input from stakeholders to understand what the original system must do and how well it must perform. The reuse of this information both expedites and guarantees the mapping process identifies a solution that will perform to the level as the original capability.

As shown, the SWx mission can utilize small satellites, such as nanosats, as an alternative to large satellites. However, low SWaP technology must exist for capabilities to be mapped. In some cases such as imagery, the required sensor or hardware may have physical limitations preventing a low SWaP solution from being developed. However, the capabilities mapping process shows that it is a realistic process. While the term capabilities is used as a target, it cannot guide the process alone. In addition, the process needs the requirements, deliverable (e.g. EDRs), and all functions that complete the capability. The capabilities mapping process separates itself from other practices such as analysis of alternatives (AoA) or trade studies by capitalizing on existing and confirmed information. The process removes the item (e.g. legacy sensor) that is no longer available (e.g. removed for cost purposes) and utilizes what has been established and confirmed by stakeholders, i.e. requirements. The requirements, specified capability, and expected deliverable enable an efficient process that develops a low cost solution. The standardized bus of the CubeSat is equally important due to cost and schedule savings.

Attention should be given to the technologies currently under development by private corporations, universities, and laboratories. Satellite sensor technologies continue

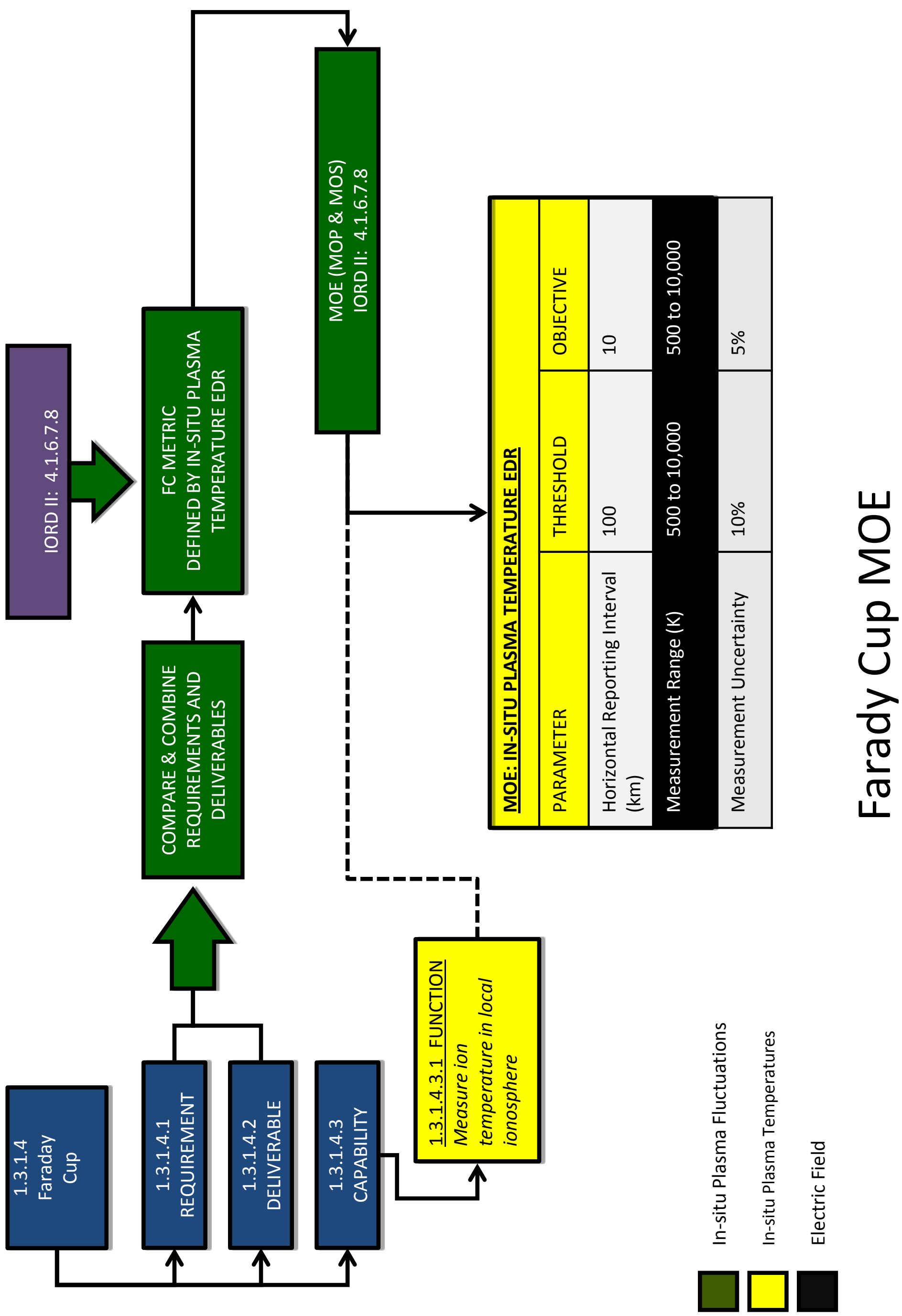
to increase in performance while their size, weight, and power are reduced. The operational success of a space weather monitoring CubeSat constellation encourages additional efforts to advance both sensor technologies and the CubeSat bus.

In conclusion, a solution to a specific capability gap has been proposed that would cost a fraction of the original system. While the low cost solution brings a shorter on-orbit life, the need for frequent replacements provides opportunities to deliver improved capabilities at lower costs. This is because the continuous manufacturing line would more easily incorporate technology advances and provide greater quantity buys as an incentive for development. Thus, every two to five years you're replacing a generation with a new more advanced system. Most importantly, the cost remains lower than in the past. The recent disbanding of NPOESS creates an opportunity to exploit small satellites and sensors as well as rethinking the way space systems are procured.

Appendix A. Selected Low SWaP, CubeSat Compatible Sensors

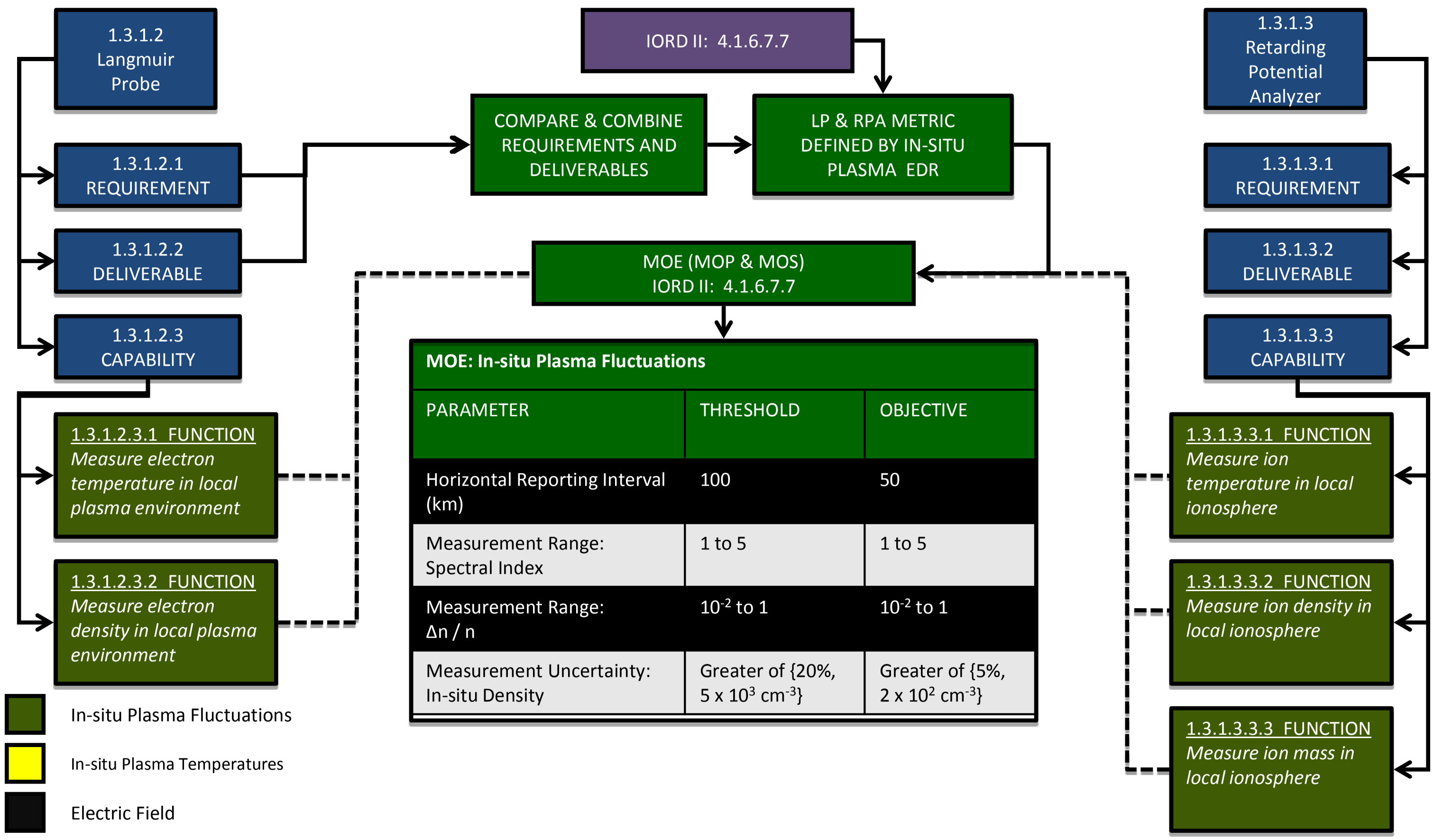
Sensor Name	Sensor Function and SWaP
Winds-Ion-Neutrals Composition Suite & Miniature Electrostatic Analyzer (WINCS+)	Measure drift (vertical/horizontal cross-track and horizontal in-track), ion density/temperature SWaP: Dimensions (cm): 7.6 x 7.6 x 7.1 Volume (cm^3): 410.1 Weight (kg): < 0.6 Power (W): < 2.3
Integrated Miniaturized Electrostatic Analyzer (iMESA) Electronics	Measure plasma density and temperature SWaP: Dimensions (cm): 7.5 x 2.5 x 1.5 Volume (cm^3): 28.1 Weight (kg): < 0.3 Power (W): < 0.8
GPS Occultation	Remote observation of ionospheric total electron content and vertical electron density SWaP: GPS Dimensions (cm): 6 x 10 x 1.3 GPS Volume (cm^3): 78 GPS Weight (kg): < 0.1 GPS Power (W): < 1 Antenna Dimensions (cm): 5.6 x 8.6 x 1.4 Antenna Volume (cm^3): 67.4 Antenna Weight (kg): < 0.15 Antenna Power (W): < 1
UV Photometer	Measure airglow and derive electron density distribution SWaP: Dimensions (cm): 10 x 10 x 15 Volume (cm^3): 1500 Weight (kg): < 1 Power (W): < 2.5

Appendix B. TPS Measure of Performance



MOE: IN-SITU PLASMA TEMPERATURE EDR

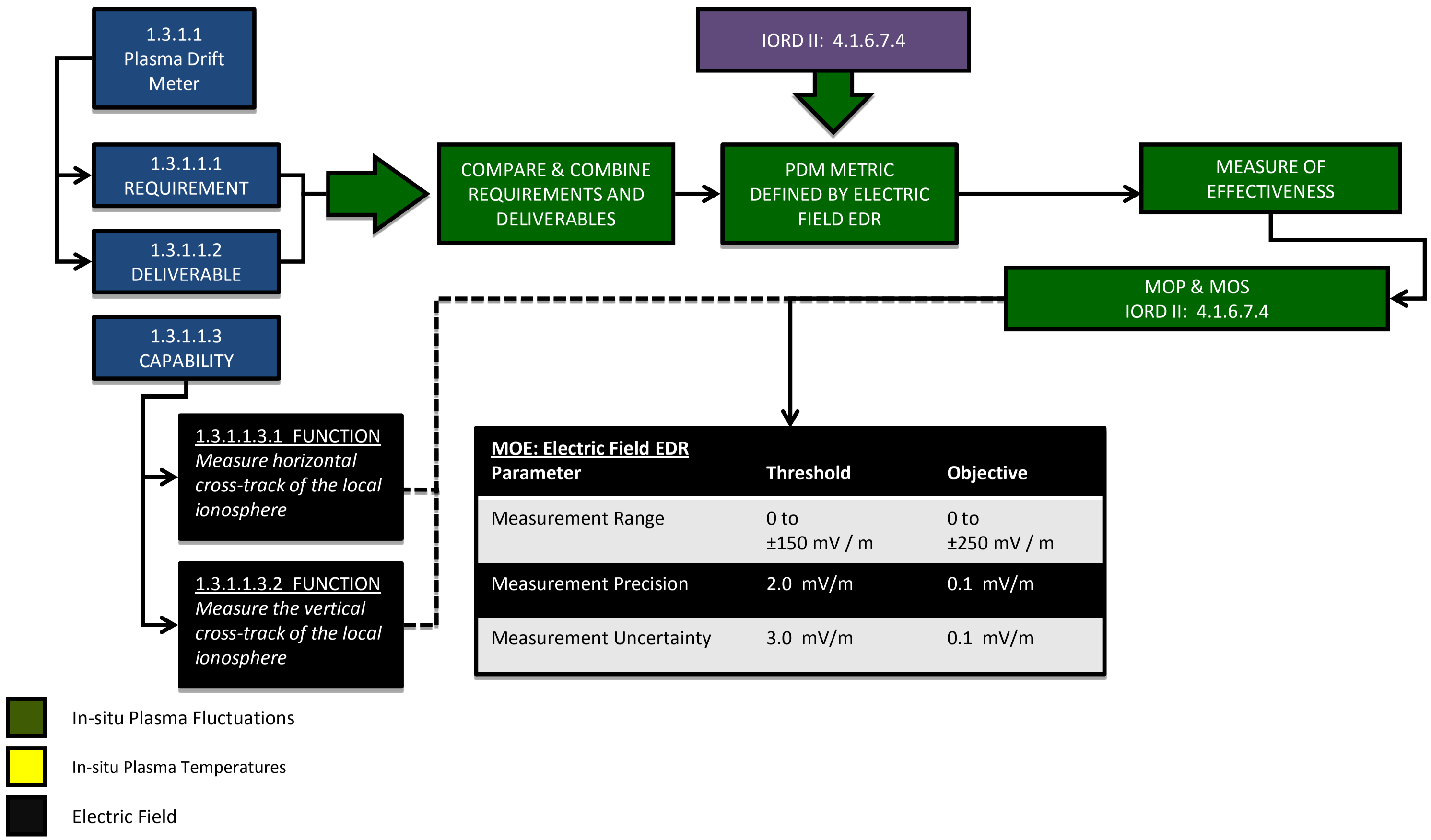
PARAMETER	THRESHOLD	OBJECTIVE
Horizontal Reporting Interval (km)	100	10
Measurement Range (K)	500 to 10,000	500 to 10,000
Measurement Uncertainty	10%	5%



MOE: In-situ Plasma Fluctuations

PARAMETER	THRESHOLD	OBJECTIVE
Horizontal Reporting Interval (km)	100	50
Measurement Range: Spectral Index	1 to 5	1 to 5
Measurement Range: Δn / n	10^{-2} to 1	10^{-2} to 1
Measurement Uncertainty: In-situ Density	Greater of {20%, 5×10^3 cm^{-3}}	Greater of {5%, 2×10^2 cm^{-3}}

Langmuir Probe and Retarding Potential Analyzer MOE



MOE: Electric Field EDR

Parameter	Threshold	Objective
Measurement Range	0 to ±150 mV / m	0 to ±250 mV / m
Measurement Precision	2.0 mV/m	0.1 mV/m
Measurement Uncertainty	3.0 mV/m	0.1 mV/m

Plasma Drift Meter MOE

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14. ABSTRACT

The cost and schedule advantages small satellites have over larger legacy systems have been studied, but there has been very little experimentation performed to determine whether small satellites can actually deliver the capabilities of larger spacecraft. To date, a desired operational capability has not been fully realized by a scalable satellite design. Advances in sensor technology have led to significant reductions in size, weight, and power (SWaP) presenting an opportunity to exploit the evolution of space operations by using small satellites to perform specific missions. This paper describes a methodology that maps a specific set of large space vehicle capabilities to CubeSats. The process examines the utility of advanced sensors.

Space weather has been identified as an excellent mission area to exploit the potential of small satellites. Advances in micro-electronics have produced sensors with reduced SWaP, making them viable test subjects. Mapping capabilities to a single or constellation of small satellites, could provide solutions and affordable options to the adverse challenges facing space operations. The methodology developed here selects sensor of the National Polar-Orbiting Environmental Satellite System (NPOESS) Space Environmental Sensor Suite (SESS) and maps them to a CubeSat illustrating a small satellite can perform an operational mission.

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